FROM THE MAKERS OF **BBC HISTORY MAGAZINE**

Collector's Edition

THE STORY OF SCIENCE & TECHNOLOGY

● The rail revolution ● Ancient Greek technology ● Brunel
Milestones in global science ● Astronomy ● The Royal Society
● Galileo ● Women of the space race ● Heroes of invention

FROM THE MAKERS OF BBC HISTORY MAGAZINE

BBC HISTORY MAGAZINE

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Calculus, chemical elements, aeronautical engineering, planetary motion, metallurgy, computing, quarks and bosons – to the layperson, the evolution of such complex concepts and technology can set the head spinning. But it's not rocket science (except, of course, rocket science!). The story of science and technology is, like all history, a narrative dominated by people, not just atoms and equations. This special edition of *BBC History Magazine* introduces the men and women whose ideas and innovations shape our world today.

We meet **Greek and Roman philosophers, mathematicians and engineers** who pioneered geometry, physics and geography – as well as gadgets ranging from automated statues to astronomical computers. And we explore the lives and work of scientists who became household names – **Plato and Newton, Galileo and Einstein**.

We also celebrate the inventors and developers of technologies that transformed the world, from **Gutenberg's printing press** to **Stephenson's steam locomotives**, and from **Ptolemy's maps** to **Ada Lovelace's insights into computing**. And we highlight the crucial contributions of less well-known scientists and researchers. Did you know that the discovery of the **DNA double-helix** hinged on the work of **Rosalind Franklin**? That Indian polymath **Jagadish Bose** revolutionised the study of **radio and microwaves**? Or that **Jocelyn Bell discovered pulsars**?

The Story of Science and Technology compiles and updates articles that have appeared previously in *BBC History Magazine*, along with several new articles written specially for this edition. I hope you enjoy it.

Charlotte Hodgman
Managing editor

"History can be a powerful ally in **teaching difficult mathematical ideas** to those encountering them for the first time"

Mathematician **MARCUS DU SAUTOY** discusses why history is inextricably linked to the study of science, on page 114

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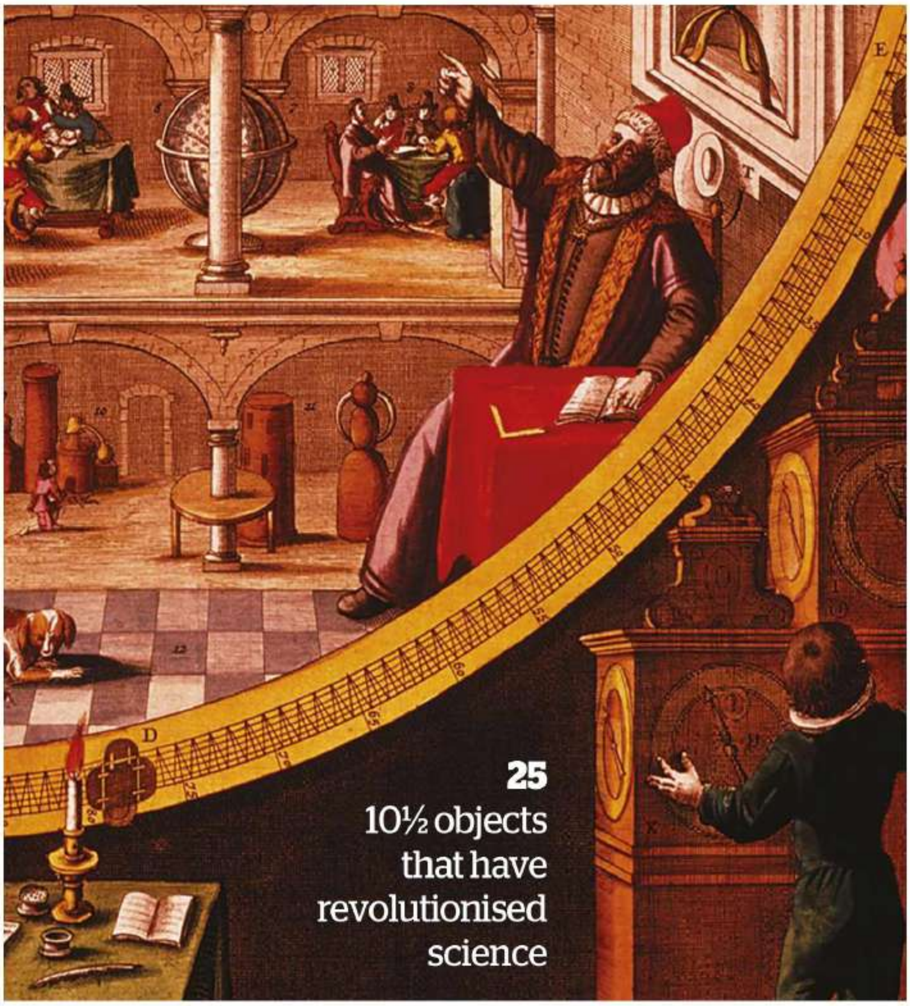

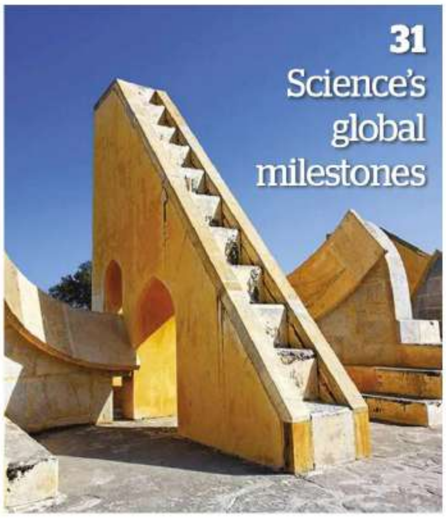

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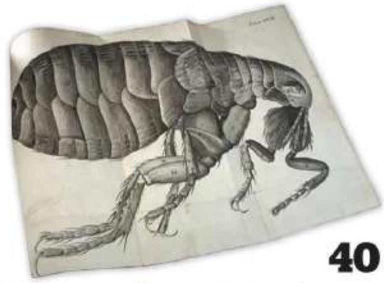

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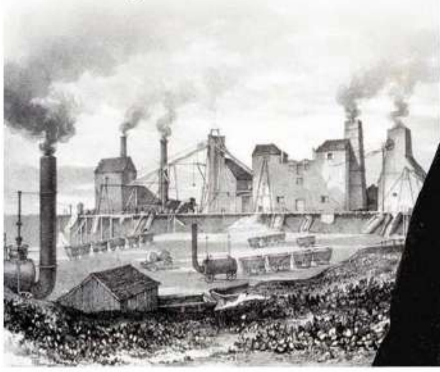

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Science stories

Patricia Fara looks at five key individuals associated with the Royal Society

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History of science

From early humans to the 21st century, **Patricia Fara** traces history's major milestones in science and technology

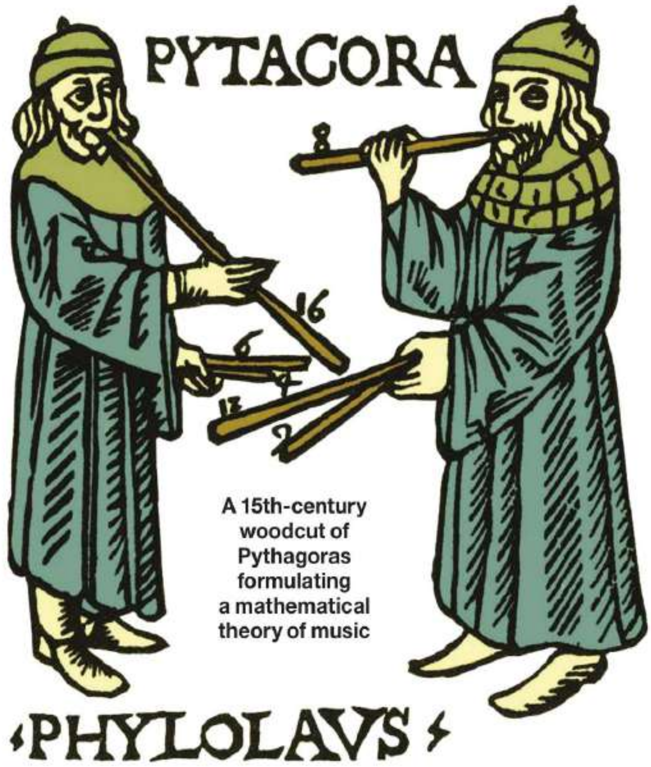
Stone tools unearthed in Kenya in 2015 predate modern humans

3.3 million years ago

The **oldest surviving stone tools** are made in Kenya by **predecessors of modern humans.**

2,100 BC

Sumerian calendars are in use, **the first ones divided into 12 lunar months.** Each begins when the new crescent moon appears at sunset. By using astronomical calculations, occasionally a 13th month is introduced to **keep the calendar aligned with the seasons**. Every seventh day is reserved for rest.



A 15th-century woodcut of Pythagoras formulating a mathematical theory of music

6th century BC

The **most famous theorem in geometry** is crucial for astronomy, building and mathematics. But although it is named after the **Greek philosopher Pythagoras,** there is no firm evidence that he proved it. In another apocryphal story, **Pythagoras is said to have mathematised the musical scale** after hearing different notes from a blacksmith's anvils.

2,000 BC **500 BC**

The discovery of cave paintings in South Sulawesi, Indonesia suggests that art may have been universal among early people

c35,000 BC

Like later examples in Europe, Indonesian cave paintings prove that **prehistoric people observed animals closely** and knew how to **make coloured materials**. Their carefully chosen locations may indicate religious rituals and beliefs.

5th century BC

According to modern science, matter is composed of tiny particles moving through empty space. **Democritus is one of the earliest Greeks to propose an atomic model,** but it is largely rejected at the time. He envisages several types of atoms – including hooked, slippery and pointed – corresponding to the characteristics of different substances.

A Greek drachma honouring the great thinker Democritus

5th century BC

A Greek philosopher from Sicily, **Empedocles (pictured below) suggests that the world is composed of four fundamental principles** or elements – air, earth, fire and water. Although they never change, they combine in different proportions to make up ordinary matter. This view **dominated scientific theories for 2,000 years.**

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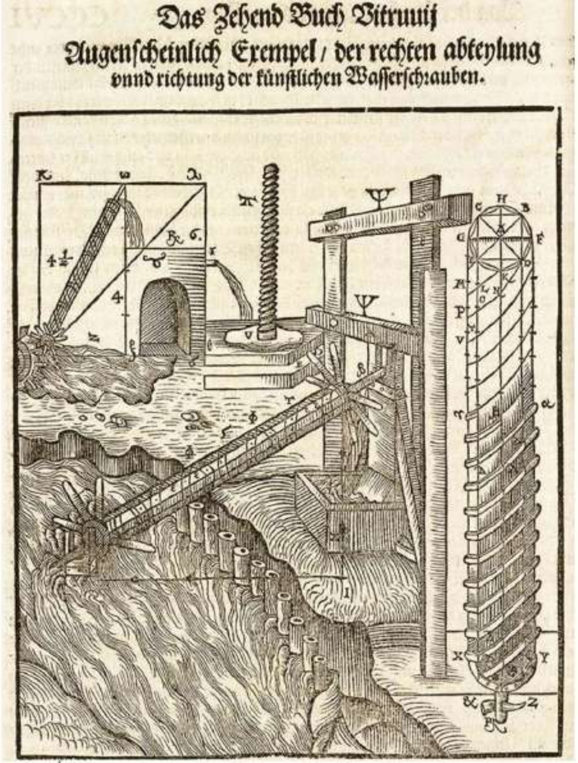


An illustration of Roman engineering feats from a 16th-century edition of Vitruvius's *De Architectura*

2nd century BC

Dramatically retrieved in the early 20th century from an ancient shipwreck, the **Greek Antikythera mechanism is a complex geared computer** used for astronomical predictions. Although its operation is not fully understood, this unique discovery **demonstrates technological expertise previously unknown** before the 14th century.

The world's oldest 'computer', discovered by sponge divers in the Aegean in 1900

1st century BC

In his celebrated books on architecture, ancient Rome's most famous engineer, Vitruvius, describes **many different technological installations, including cranes, aqueducts, catapults, water clocks and central heating systems.** He also discusses Archimedes' giant screws, used in farming and mining to raise water from one level to another.

2nd century AD

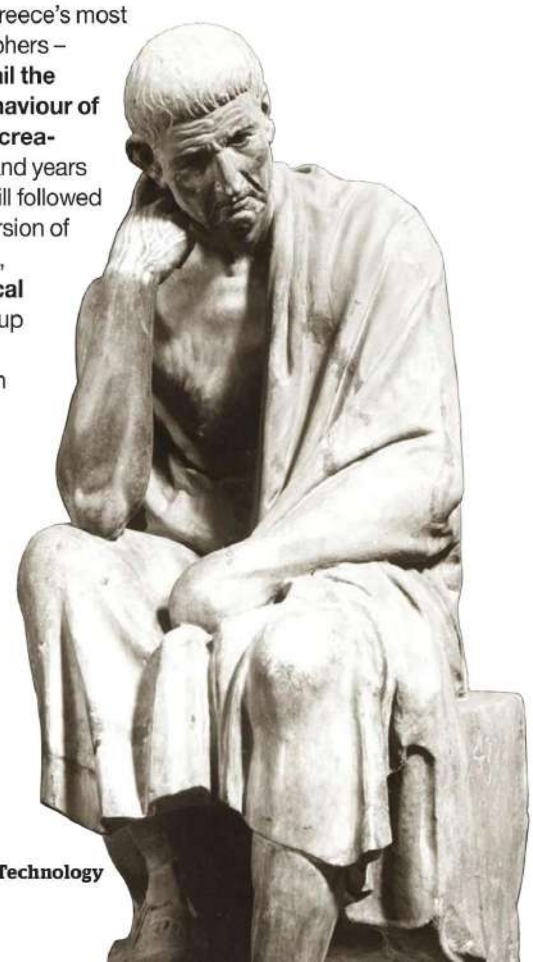
Writing in Greek, Claudius Ptolemy of Alexandria produces his *Almagest*, a **mathematical and astronomical treatise describing an Earth-centred universe.** It is extremely influential throughout the Islamic empire and Renaissance Europe. By introducing convoluted orbits called epicycles, Ptolemy tries to explain why some planets appear to travel backwards intermittently.

400 BC

1 AD

4th century BC

In his *History of Animals*, Aristotle – one of ancient Greece's most influential philosophers – **describes in detail the anatomy and behaviour of several hundred creatures.** Two thousand years later, naturalists still followed a Christianised version of his chain of nature, **a fixed hierarchical ladder** stretching up from the lowliest organisms through birds, animals and humans towards angels and God.



Aristotle's plan of over 500 living beings was based on detailed zoological research

1st century AD

Pliny writes his *Natural History*, a comprehensive encyclopedia of Roman knowledge. Divided into 37 books, it encompasses an enormous range of subjects. One of the first ancient books to be printed in the Renaissance, its wide range made it the **standard work of reference for many centuries.**

Pliny's work aimed to collect together all ancient knowledge of geology, zoology, astronomy and art

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c800

The House of Wisdom flourishes in Baghdad from the 9th to the 13th centuries. Financially supported by the caliphate, **scholars translate Greek texts into Arabic** and also carry out further research. These **improved Islamic versions of Greek knowledge** provided crucial foundations for the European Renaissance.

***The Book of Ingenious Devices*, compiled by three Iranian brothers in the House of Wisdom, AD 850**

1439

When **Johannes Gutenberg introduces his printing press with reusable letters,** he revolutionises European scholarship by **enabling new ideas to be reproduced accurately and disseminated quickly.** Once books had become affordable, scientific knowledge could spread all over the world.

800

1100

c850

Gunpowder, made by mixing three chemicals together, is the earliest known manufactured explosive. Like many other technological inventions, it is first **referred to in China centuries before appearing in Europe.** Gunpowder is used in mining and fireworks as well as in weapons.

Tang dynasty emperors used gunpowder to put on fireworks displays

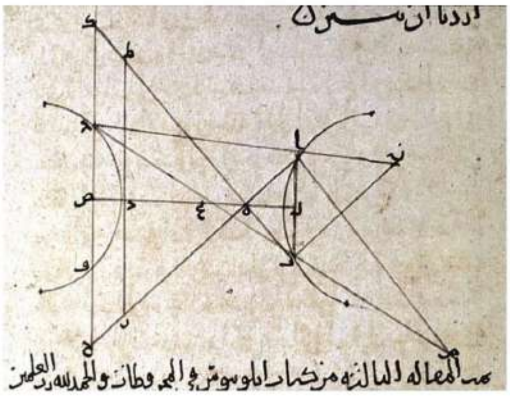

Diagram showing a mathematical analysis of vision by Ibn al-Haytham, pioneer in the study of optics

1011-21

The Muslim scholar Ibn al-Haytham (Latinised as Alhazen) introduces the **theory that vision depends on light being reflected from objects.** He synthesises three older approaches – Greek geometry, classical anatomy and Aristotle's suggestion that objects transmit messages into the eye – but **rejects Ptolemy's idea that the eye emits rays of light.**

1150s

Central Europe's most significant natural historian during the 12th century is an abbess, **Hildegard of Bingen** who learns from her personal practical experience as a herbalist. She is now more famous for her music and her visionary theology, but **her two books on medicines and diseases are important for revealing the concealed world of female healing.**

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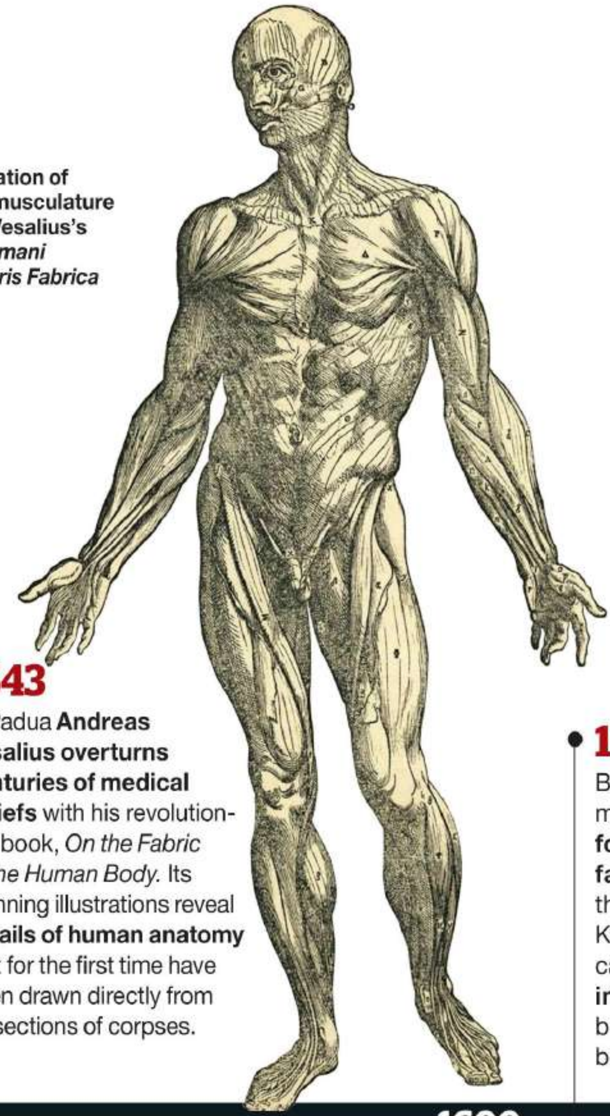


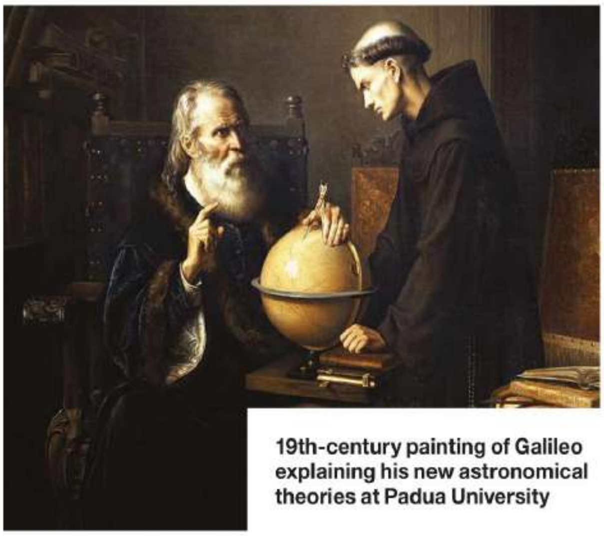
Illustration of male musculature from Vesalius's *De Humani Corporis Fabrica*

1543

In Padua **Andreas Vesalius overturns centuries of medical beliefs** with his revolutionary book, *On the Fabric of the Human Body.* Its stunning illustrations reveal **details of human anatomy** that for the first time have been drawn directly from dissections of corpses.

1619

By 1619, the German astronomer **Johannes Kepler has formulated all three of his famous laws.** Employed in the imperial court at Prague, Kepler describes mathematically **how the planets rotate in elliptical orbits.** He also believes that the universe is bound together magnetically.



19th-century painting of Galileo explaining his new astronomical theories at Padua University

1633

Galileo is sentenced to house arrest after his sensational book, *Dialogue Concerning the Two Chief World Systems* (1632) challenges Christianity by supporting a heliocentric system. His telescope has enabled him to collect incontrovertible evidence – such as the movement of Jupiter's moons, and that the Earth moves around the Sun.

1600

1543

In his Latin *On the Revolutions of the Heavenly Spheres*, the Polish priest Nicolaus **Copernicus (pictured below) suggests that the planets rotate in circles around a central Sun.** This idea is not immediately accepted: many mathematicians regard it as a geometric model rather than physical reality, and it cannot be proved experimentally.

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1572

After a bright star suddenly appears in 1572, **the Danish astronomer Tycho Brahe carefully measures its location.** By proving that it lies beyond the Moon's orbit, he challenges the Aristotelian belief that the heavens are unchanging. The observations from his Uraniborg observatory would go on to **prove crucial for establishing Copernicanism.**

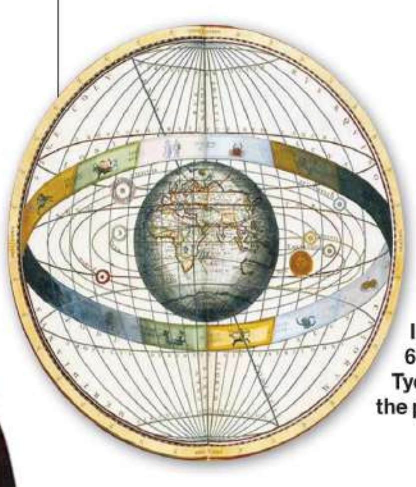


Illustration (1660–61) by Cellarius of Tycho Brahe's plan of the planets' orbits

1628

For centuries, doctors believed that the liver constantly generates blood. Through carrying out quantitative experiments, the royal physician **William Harvey shows that the heart repeatedly pumps a fixed amount of blood around the body.** He also studies reproduction, arguing against the possibility of spontaneous generation.

1644

In his Latin *Principles of Philosophy*, the French philosopher René Descartes (pictured above) eliminates mysterious powers from the universe by describing **a mechanical universe packed with tiny moving particles** that repeatedly collide with each other. He formulates Newton's first law of motion: without intervention, objects move uniformly in straight lines.

1660
London's Royal Society is **among the first organisations being established to exchange scientific information through an international network.** In contrast with university scholars, their members emphasise the importance of instruments and experiments, and demonstrate how scientific research can be practically and commercially valuable.

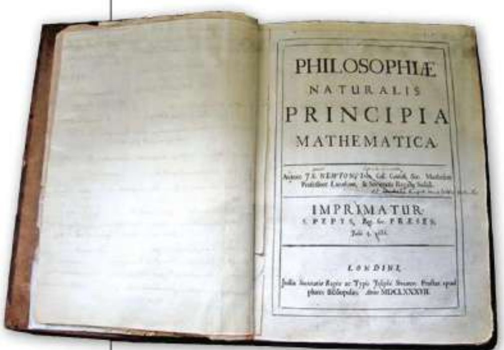
1705
Benefiting from a Dutch grant to study the flowers and insects of Suriname, Maria Sibylla Merian (pictured above) is **one of the earliest explorers to travel with a solely scientific mission.** Her beautiful illustrations and meticulous investigations make her a founding figure in the science of entomology (the study of insects).

1735
The Swedish Carl Linnaeus (pictured below) introduces a **two-part classification scheme for plants** based on counting the female pistils and male stamens in flowers. Although easy to use, **its focus on sexual organs make it controversial.** He later extends his binary system to animals, inventing labels such as *Homo sapiens.*

A Montgolfier brothers poster for one of their wildly popular balloon demonstrations, where visitors could witness untethered flight

1783
Hot air balloons invented by the French Montgolfier brothers **enable human beings to fly for the very first time and cause an international sensation.** Symbolically signifying the progress of science in an era of revolutionary politics, they are later used for research into the atmosphere.

1700

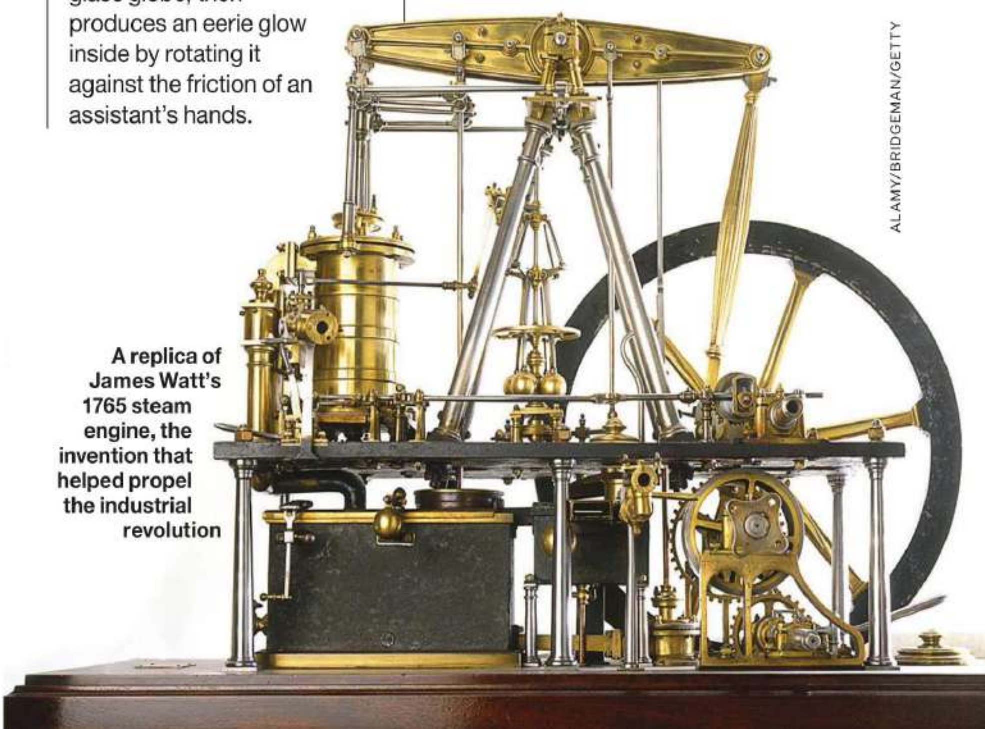


Newton's own annotated copy of the *Principia Mathematica*

1687
Building on the innovations of his predecessors, in his *Mathematical Principles of Natural Philosophy* **Isaac Newton makes mathematics central to science.** He sets out his **three laws of motion,** and introduces gravity to integrate the Earth within the heavens by a single principle of attraction varying with distance.

1706
The world's **first electrical machine is invented by Francis Hauksbee,** a former draper, to entertain the fellows of London's Royal Society. Hauksbee pumps the air out of a glass globe, then produces an eerie glow inside by rotating it against the friction of an assistant's hands.

1765
Steam engines had long been used to pump water out of Cornish mines, but by **inventing a separate condenser**, James Watt makes them far more efficient: they use less coal to produce the same power. **Watt's steam engines drive the factories and trains** of the industrial revolution that makes Britain wealthy.



A replica of James Watt's 1765 steam engine, the invention that helped propel the industrial revolution

1800

Machines have been generating static electricity for almost a century, but **Alessandro Volta's pile or battery produces continuous current electricity for the first time.** It stimulates experimenters to isolate new elements, such as sodium and potassium, and to split water into its two component elements: hydrogen and oxygen.

1831

The possibility of transforming motion into electricity is discovered by Michael Faraday (pictured above), the son of a blacksmith, who made many other important discoveries. Electromagnetic induction came to lie at the heart of the modern electrical industry. Having initially studied science in his spare time, he **later becomes director of the laboratory at the Royal Institution.**

1800

A 1788 portrait of chemistry pioneers Marie and Antoine Lavoisier

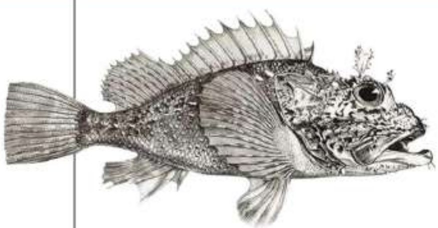
1789

The French tax collector **Antoine Lavoisier publishes the first textbook on chemistry.** He is celebrated for insisting on precise measurement and **systematising the way chemicals are named**. The book's accurate technical diagrams, drawn by his wife, Marie, are essential for transmitting the new chemistry internationally. Lavoisier is guillotined during the French Revolution.

1811

Uneducated and from a poor family, Mary Anning is 12 when she **discovers the nearly complete skeleton of what came to be called an Ichthyosaurus** at Lyme Regis. Soon wealthy collectors from London take advantage of her paleontological expertise to examine dinosaur skeletons that **dramatically change ideas about the past.**

Mary Anning found fame by discovering Jurassic fossils



A scorpion fish, one of the species Darwin studied on his voyages on HMS *Beagle*

1859

Charles Darwin publishes *On the Origin of Species*, having spent many years collecting **evidence for his theory of evolution** by natural selection, later summarised as 'the survival of the fittest'. By this time, many people have already accepted that the Earth is extremely old.

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Reproduction of Mendeleev's 1869 Periodic Table, including gaps

1869

The Russian chemist Dmitri Mendeleev **organises the elements into the Periodic Table** and predicts ones that have not yet been discovered. Reading across the rows, the atomic number increases one at a time; in the vertical columns, elements with similar properties are grouped together.

Radio pioneer Marconi with apparatus similar to that he used to send the world's first ever wireless communication over open sea

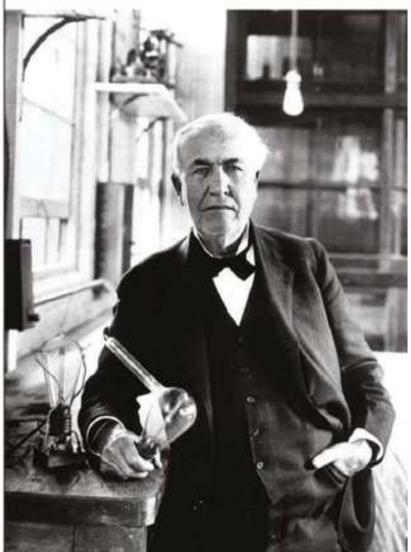
1897

While physicists are investigating the **scientific properties of radio waves,** Guglielmo Marconi becomes the first to realise their **commercial potential for long-distance communication using Morse code.** Unable to get Italian funding, his earliest successful messages are sent in Britain.

1910

Pure metallic **radium is first isolated** by Marie Skłodowska Curie, a Polish woman living in Paris. The first winner of two Nobel Prizes, she investigates pitchblende ore, which is rich in uranium salts, to make the novel suggestion that radioactivity comes from inside atoms. **The discovery of radium revolutionised cancer treatment.**

1900



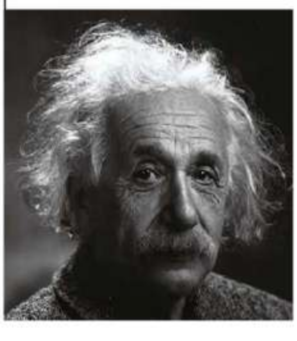
Edison photographed in c1910 with an early light bulb, one of 1,000 inventions he patented

1879

Prolific inventor Thomas Edison **devises a commercially viable electric light bulb** that can be cheaply produced, lasts a long time and uses relatively little power.

1905

Albert Einstein (pictured below) is working in the Swiss patent office when he formulates his theory of special relativity, including the notion that time appears to stretch at high speeds. **His famous formula $E=mc^2$ underpins the atomic bomb** and shows that a small change in mass can release vast amounts of energy.



Depiction of Wegener's theory of Pangea fragmenting into the continental landmasses

1912

When the German meteorologist Alfred Wegener suggests that **a single original landmass called Pangea had slowly split apart,** few scientists believe him. He is only vindicated in the 1950s, when magnetic measurements made beneath the Atlantic Ocean **confirm Wegener's theory of continental drift.**

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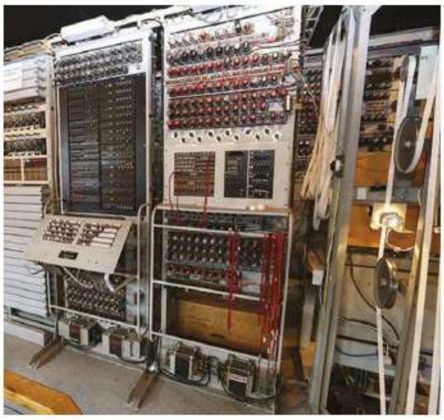

Reading up to 5000 characters per second, the Colossus computer broke codes used by the German high command

1944

The **world's first programmable, electronic digital computers become operational at Bletchley Park,** where they are used to decode German military intelligence messages. Built in secret, **their significance goes unrecognised for decades.**

1945

Led by military officials, teams of scientists scattered across the US work secretly to **develop the world's first atomic bombs** before the Germans. Two are dropped over Japan, ending the Second World War **but leaving a lasting radio-active legacy.**

1950

1953

Determined to get there first, James Watson and Francis Crick rely on an X-ray diffraction photograph taken by Rosalind Franklin **to work out the double helix structure of DNA.** Unique to every individual, these twisted molecular strands carry the **genetic information essential for life, growth and reproduction.**

1967

As a postgraduate student at Cambridge, at first Jocelyn Bell finds it hard to convince her supervisors that the small blips she observes on computer print-outs are significant. **She had discovered pulsars, rotating neutron stars that regularly emit beams of radiation and provide valuable celestial clocks.**

Postgraduate astronomy student Jocelyn Bell detected the pulse of rapidly rotating neutron stars

US astronaut Buzz Aldrin is photographed by Neil Armstrong during the first manned lunar mission

1969

After an intense Cold War space race against Soviet Russia, the American **Neil Armstrong becomes the first human being to walk on the Moon.** Claiming to have come in peace for all the world, he collects soil samples and plants the Stars and Stripes.

2000

2012

After a 40-year search, scientists searching for the **elusive Higgs boson particle, finally track it down with the Large Hadron Collider** at CERN in Switzerland. This was a major triumph for particle physicists, because the boson's existence demonstrates **the validity of other theories known collectively as the Standard Model.** H

Patricia Fara is president of the British Society for the History of Science and the author of *Science: A Four Thousand Year History* (Oxford University Press, 2009)

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IDEAS & IN

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  Ingenious inventions from antiquity
- **What the Romans *really* did for us**
  How many Roman innovations were really new?
- **Science stories: Gowin Knight's compass**
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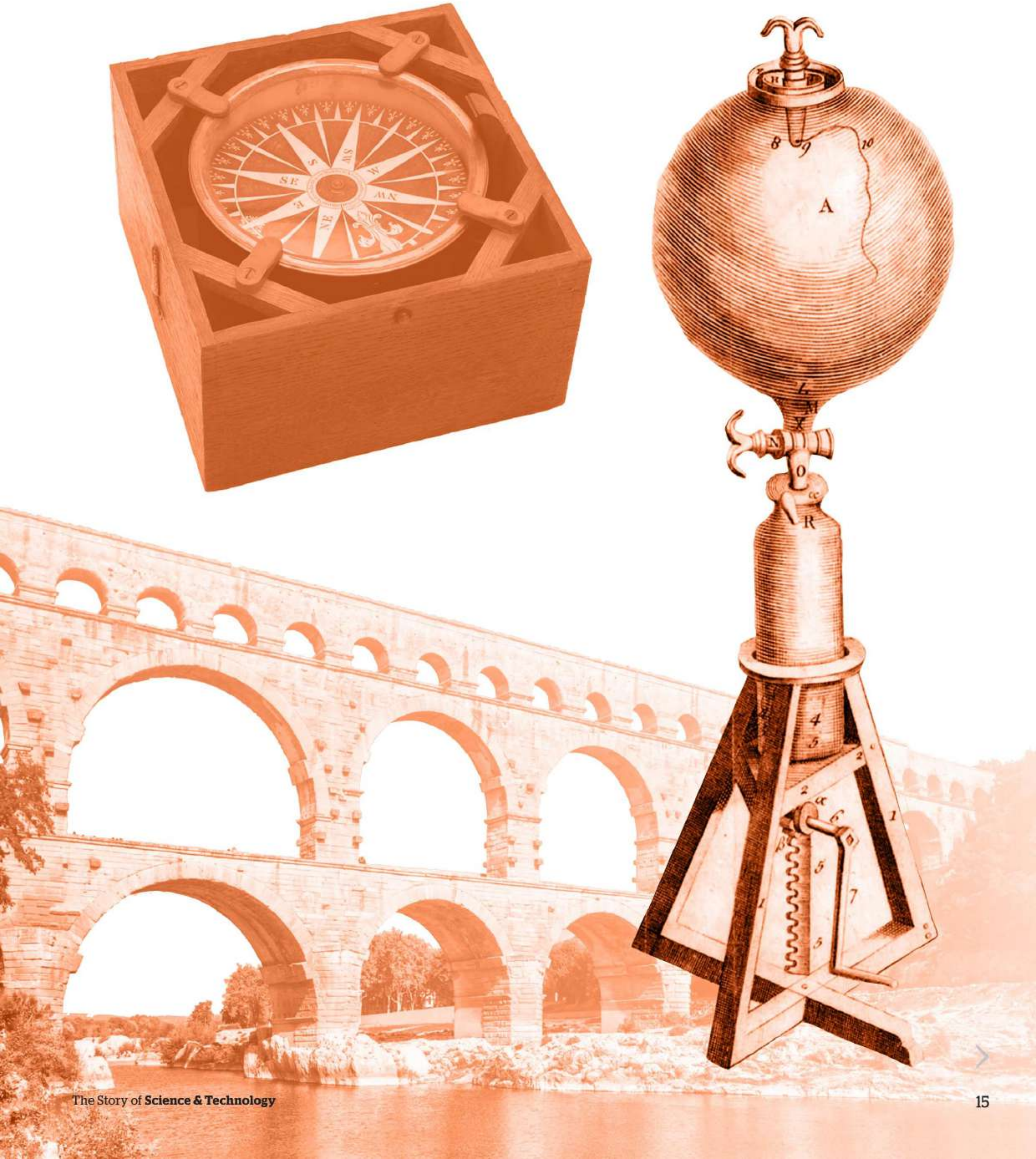
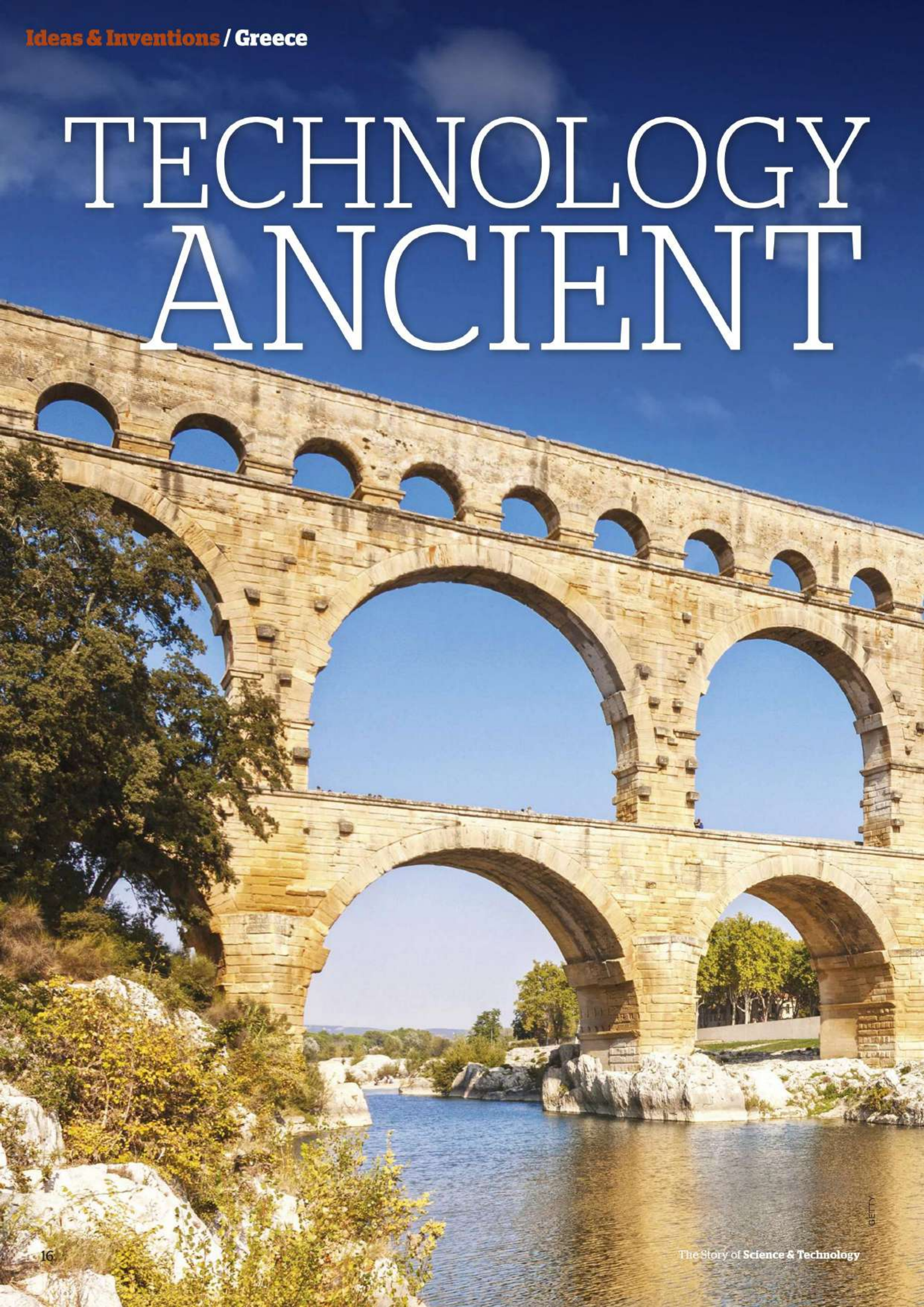
VENTIONS



TECHNOLOGY ANCIENT



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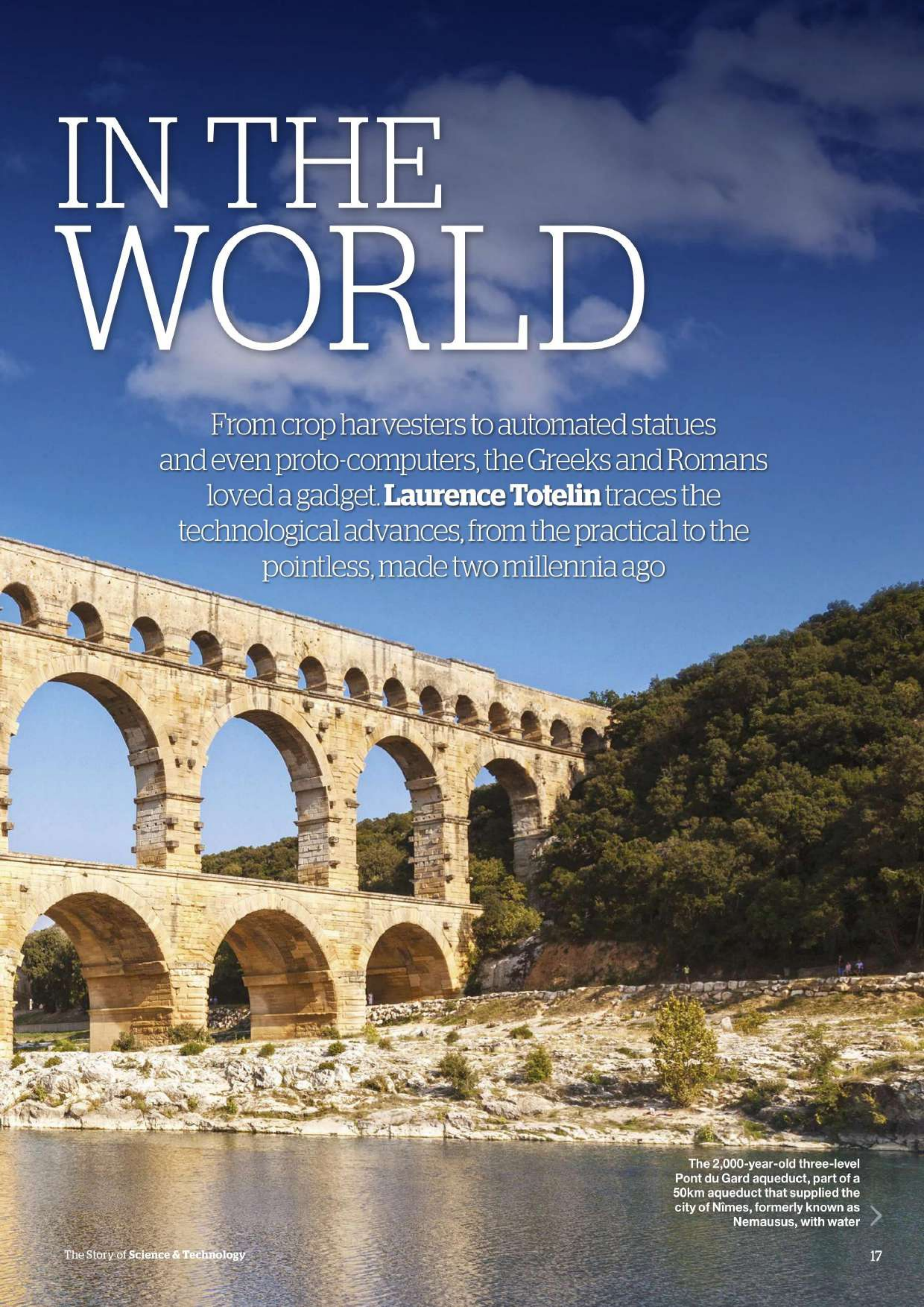
IN THE WORLD

From crop harvesters to automated statues and even proto-computers, the Greeks and Romans loved a gadget. **Laurence Totelin** traces the technological advances, from the practical to the pointless, made two millennia ago



The 2,000-year-old three-level Pont du Gard aqueduct, part of a 50km aqueduct that supplied the city of Nîmes, formerly known as Nemausus, with water

A modern recreation of the 2,100-year-old Antikythera mechanism, the clockwork 'computer' recovered from the Mediterranean as a single encrusted piece (right) in 1901. Featuring around 35 gear wheels, it is thought to have been a highly sophisticated device to predict celestial movements, such as solar and lunar eclipses

In 1901, a large lump of corroded bronze was recovered from a shipwreck off the coast of the Greek island of Antikythera. The ship had sunk in the first century BC and had been carrying a varied cargo which included precious jewellery, glassware and statues. The metal lump, perhaps unsurprisingly, did not spark interest at first. However, it came to light that it contained gear wheels and deserved further research.

Over a century after its discovery, what is now known as the Antikythera mechanism is considered the finest example of ancient Greek technology. This proto-computer contains over 35 gear wheels; it predicted eclipses, tracked various ancient calendars, traced the positions of celestial bodies on the ecliptic, and much more beside.

Who could have created such a device? Recently, scholars have suggested that Archimedes, one of the most famous scientists of antiquity, might have been responsible. Indeed, the mathematician had created celestial globes, one of which had been deposited by the Roman general Marcellus at the Temple of Virtue. While it is tempting to associate the Antikythera mechanism with a prominent scientist, it is probably wisest to suggest that several people in the ancient Mediterranean had the skill and knowledge to devise such a wonderful machine.

It was the ultimate gadget: an instrument of **extreme precision but of limited practical utility**

The Antikythera mechanism could be compared to a very expensive modern clock or watch, with its numerous dials that the owner may rarely use. It was the ultimate gadget: an instrument of extreme precision but of limited practical utility. Ancient Greek texts describe several such gadgets. The mathematician and engineer Hero of Alexandria (first century AD) describes a miniature temple with automated doors, activated by steam, as well as a self-trimming oil lamp. On a grander scale, automated statues were created in the Hellenistic period (323 BC–31 BC). An account of the Ptolemaia, a lavish festival in honour of King Ptolemy II and his wife Arsinoe II, mentions a statue of the goddess Nysa that could rise and sit automatically, as well as pour libations of milk. When studying ancient technology, it is important to consider these gadgets, as they show the crucial role wealthy patrons played in technological innovation. These patrons enjoyed showing off to their guests with their entertaining devices, but showed relatively little interest in developing what we would consider to be more useful machines.

Technology for the many

Of course, many important technologies were developed in the ancient Graeco-Roman world. Kings, tyrants and emperors invested into warfare technologies, leading to the development of powerful and precise catapults, such as the *carroballistas* depicted on Trajan's Column in Rome. Archimedes is credited with the invention of the eponymous screw, a device that carries a substance from a lower to higher point. The Romans are renowned for their extensive water transporting systems, with their majestic aqueducts. These systems, described in detail by the author Frontinus (first century AD), alimented fountains and baths, the latter also benefitting from underfloor heating systems (hypocausts). The Romans also harnessed the power of water in mining. At Dolaucothi gold mines in west

GETTY

Wales, for instance, they built vast tanks to hold water, which would sweep away soil and reveal gold veins in the bedrock when released. In addition, the Romans created concrete that resisted the test of time, the recipes for which are preserved by the author Vitruvius (first century AD).

Focusing on epoch-making innovations and inventions, however, is not always productive in the history of technology, for it distracts from everyday technologies which played a crucial role in the lives of the many rather than the few. It is worthwhile to take a step back and reflect on the meaning of the word 'technology', which is Greek in origin.

'Technology' is a discourse (Greek: *logos*) about a *technê* (plural *technai*) – a word that can be very difficult to translate into English, although 'art' or 'craft' are often appropriate. Greek philosophers, especially those who had studied with Socrates, reflected at length on the notion of *technê* and its relationship with *epistêmê*, knowledge. Thus, Plato often used examples from *technai* to illustrate philosophical points: from farming, sculpting, weaving, pottery, horsemanship, music playing, generalship, cookery, medicine, and many more. The philosopher also questioned whether certain arts, such as rhetoric, should count as *technê* or not. Many of the *technai* listed by Plato changed relatively little over the course of antiquity, but nevertheless were essential to the good functioning of society.

Ancient *technai* were usually transmitted along family lines, generally from father to son or from mother to daughter. They were a source of pride to those who possessed them. The Hippocratic Oath (a text that is very difficult to date, but may go back to the fifth century BC) illustrates this feeling of pride: the new doctor who swore the oath (by no means all doctors swore it in antiquity) promised to 'guard my life and my *technê*'. If he did so, he would benefit from good returns and excellent reputation.

Written in wax

Ancient potters active at Athens at the beginning of the fifth century BC enjoyed representing other artisans' *technai*. For instance, the so-called Foundry Painter depicted a bronze workshop in great detail on the 'Foundry Cup': the smelting oven, statues at various stages of build, and separate bronze hands and feet, ready to be attached to statues. The Clinic Painter, for his part, represented a doctor's surgery on an *aryballos* (a small flask): a physician bleeding a patient, while others queued outside. Finally, Douris, on his School Cup, painted a school, where both music and reading were taught.

Writing itself is a technology, one that involves tools and skills. Neither the Greeks nor the Romans invented writing, but the Greeks were the first to write down vowels, adapting the Phoenician alphabet (or to be more accurate *abjad*), which only contained consonants, to the needs of their language in the late ninth or early eighth century BC. Greeks and Romans used a variety of media for writing, including wax tablets and papyrus scrolls, both represented on Douris's School Cup. The papyrus scroll, made from the plant of the same name, was the material on which the books of the famous Library at Alexandria were preserved.

Legend has it that parchment was invented in the second century BC at Pergamum. The kings of Pergamum, the Hellenistic Attalids, wanted to create a library that would rival that of Alexandria. To do so, however, they needed papyrus, which grew only in Egypt. The Ptolemaic kings based at Alexandria refused to export the precious plant, which led the kings of Pergamum to develop an alternative: prepared skins of animals. That story, however, is unlikely to be true, as parchment is attested in Anatolia several centuries earlier.

While the scroll (whether of papyrus or parchment) remained in common use throughout antiquity, it gradually lost its prominence to the codex, which resembles the books with which we are familiar. First mentioned in the first century AD, the codex started to rival the scroll in the second century AD. Initially it was favoured by marginal groups, such as the early Christians who used it for their devotional works, but it slowly gained popularity, and became the dominant format by AD 500.

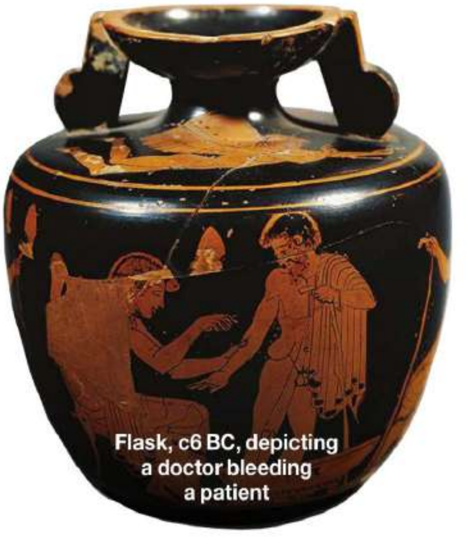
Technology, then, should not be confused with engineering, which is only one branch among many. Some technologies, such as precision gear tools, remained in the hands of the wealthy. Others, such as water transportation technologies, benefitted a larger section of the ancient population, although by no means everyone. But perhaps most important in shaping our perception of the ancient world is writing, even though levels of literacy remained relatively low throughout antiquity. **H**

Laurence Totelin is a senior lecturer in ancient history at Cardiff University and the author, with Gavin Hardy, of *Ancient Botany* (Routledge, 2015)

Technology in Greek and Roman agriculture

There were relatively few major innovations in agriculture during classical antiquity. The watermill, first invented in the Hellenistic period, became increasingly common in late antiquity, and archaeological remains have been found throughout the western Roman empire. Two Roman authors, Pliny the Elder (first century AD) and Palladius (fourth or fifth century AD) describe a harvesting machine, called a *vallus*, sometimes dubbed the 'ancestor of the combine harvester', employed on large estates in Gaul. It was mounted on wheels, pulled by an ox, and was equipped with metal teeth to cut off the ears of corn. An exceptional representation of the harvester was discovered in Buzenol in Belgium in 1958. Sixty years later, scholars still debate about the exact appearance and function of the *vallus*.

While mechanical inventions were few, if we accept a broader definition of technology, one that includes various crafts and skills, there were some important agricultural advances in classical antiquity. In particular, the Romans perfected the art of tree grafting, the joining of a scion to a rootstalk, which is essential in propagating fruit trees that are not productive when growing from seed. Grafting methods allowed the Romans to transplant fruit trees from central Asia to the Mediterranean basin, and hence to northern regions. For instance, the Romans propagated the sweet cherry that grew in Pontus (modern Turkey) to Italy, and then to Roman Britain. They also perfected techniques to 'graft' together trees that are not compatible – to be compatible, trees must be of the same genus, preferably of the same species. Thus, the agronomical writer Columella (first century AD) describes at length how he developed a method to 'graft' an olive onto a fig. From the point of view of modern botany, this was not truly a graft (where scion and rootstalk end up sharing vascular tissue), but rather a method in which the olive took root in the fig. Still, it was a great feat of horticultural skill.



Flask, c6 BC, depicting a doctor bleeding a patient

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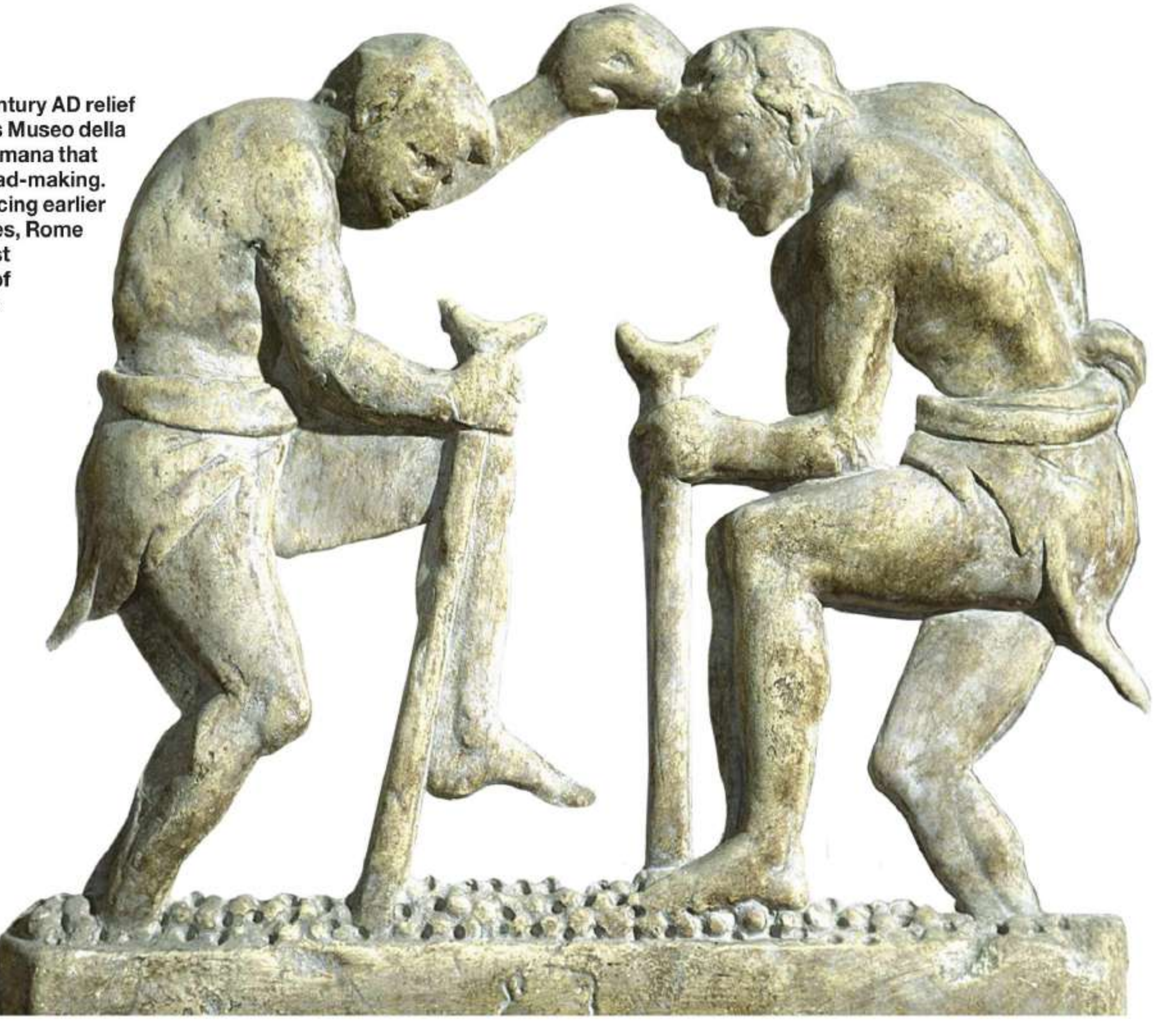
INVENTION OR ADAPTATION?

WHAT THE ROMANS *REALLY* DID FOR US

The Romans get the credit for a lot of inventions, but do they deserve it? **Jem Duducu** investigates how Roman innovation was often a case of adaptation, rather than originality...



A first-century AD relief at Rome's Museo della Civilta Romana that shows road-making. By enhancing earlier techniques, Rome built a vast network of highways

BRIDGEMAN

Giulio Romano's fresco, 1526–35, depicting the Roman gods Mars (Ares to the Greeks) and Venus (Aphrodite) – the Romans liberally adopted Greek mythology

▲ IMITATING THE GREEKS

The Romans copied the Greeks... a lot. As their powerful predecessors fell, Rome freely incorporated Greek culture

Roman civilisation only really got into its stride in the third century BC. By then, the Greeks had been cultivating their culture for centuries. In the second century BC, Macedonia was the main military power in the Greek world, but Rome was a greedy neighbour and fought four separate wars against it. By 146 BC, Macedonia and the rest of the Greek world had fallen under Roman rule.

Roman architecture is an interesting example of Greek influence. The very first structures in Rome were circular, implying a Celtic influence, but over time that all changed. Instead, the columns and triangular pediments that had been all the rage in Greece for centuries began to emerge.

Another example of the Greek influence on Rome is the pantheon of gods, renamed by the Romans but, in terms of myths and imagery, completely interchangeable with the Greek gods. Zeus was Jupiter and Ares was Mars, while soothsayers and oracles both also appeared in Greek culture.

The Greek Olympic Games flourished under Roman rule and even chariot racing seems to have originated in Greece.

◀ ROMANS ROADS

Straight, paved, well-drained – Rome's superhighways weren't the first, but they made the world's most extensive network

In the fifth century BC, King Darius of Persia ordered the construction of the 'Royal Road', which stretches over 1,600 miles – but not all of it was paved, nor was all of it straight. The oldest *paved* road in history is in an Egyptian quarry and is around 4,600 years old.

The Romans could see potential in these early roads, so they borrowed the idea and enhanced it. At the peak of the Roman empire there were 29 military highways radiating from the capital, with 113 provinces interconnected by 372 roads – nearly a quarter of a million miles in total. At the time, and for years to come, this was the best-connected empire the world had ever seen.

Straight, paved roads improved communication, trade and the movement of armies. However, they were also expensive to build and maintain. Only 20 per cent of Roman roads were paved in stone, meaning that 80 per cent were either dirt tracks or covered only in gravel, which degraded over the winter months. Even the stone roads weren't always all that great. In the Vindolanda Tablets – a series of 'postcards' written on slivers of wood and discarded at a Roman fort on Hadrian's Wall – it is interesting to read complaints about the state of the roads that the soldiers travelled on, demonstrating that maintenance wasn't always a priority.

AKG IMAGES

CONCRETE FEAT

The Romans (sort of) invented concrete, the quick and cheap material that helped build the empire

There is a form of concrete that is naturally occurring, so technically it predates humans. Yet in around 1200 BC, the Mycenaeans made floors in concrete. Independently, Bedouins in north Africa also created their own concrete before the Roman era.

However, it was the Romans who were to use concrete – made from a mixture of water, quicklime, sand and volcanic ash – extensively and consistently from around 300 BC right up to the fall of Rome in the fifth century AD. Indeed our word 'concrete' comes from the Latin *concretus*, meaning 'compact'. Somewhat confusingly, the Romans themselves didn't use the Latin word *concretus*; they called it *opus caementicium*.

The Romans recognised that building arches and domes using a quick-drying, liquid material was far easier than trying to build the same features in brick or stone. It was far cheaper and quicker than building a large structure from solid marble too. It was also the Romans who developed the idea of making a framework in concrete, before cladding it with stone. The Colosseum in Rome is an example of a large, mainly concrete, Roman structure.

Emperor Augustus famously said: "I found Rome a city of bricks and left it a city of marble." While this may be a great line that underscores his achievements as emperor, he missed out the most important Roman building material of all – concrete.

▲ SIEGE WARFARE

Engineering savvy and superior weaponry meant the Romans were masters of siege warfare

The Romans didn't invent siege warfare, but they certainly mastered it. It is fair to say that if Roman legions made it as far as an enemy city or fort, the defenders were at a disadvantage, no matter how high or how thick their walls. Alongside brutal tactics, the Romans had a number of weapons to bring a siege to a successful conclusion.

One of these deadly tools was a *ballista* (what the modern world would call a catapult), which hurled stones or sometimes pots of Greek fire, the ancient equivalent of napalm. Depending on circumstances, *ballistas* could also be mounted on warships. The Romans were exceptional engineers who could usually determine the weak spots in defenders' walls and would keep pounding them until they came down. A later version of the *ballista* was called an *onager*, which did pretty much the same job but was cheaper and easier to build.

The *scorpio*, meanwhile, was like a large version of a crossbow. It could fire bolts over long distances (well out of the range

▼ COUNTING THE DAYS

Julius Caesar brought time into line with a 12-month calendar that would provide stability for centuries

The Julian calendar was not the first calendar, but has been the most influential in European history. Julius Caesar didn't put his name to the months, however; this was done later in his honour. The old *Quintilis* was changed to *Iulius* (July) and the eighth month became known as *Augustus* (August).

The Julian calendar, brought into effect by Caesar in 45 BC, has a regular year of 365 days, divided into 12 months, with a leap day added to February every four years. This system worked well for over a millennium.

However, the year isn't exactly 365¼ days long. Although this was only a tiny discrepancy, over the centuries it began to cause problems – the calendar year gained about three days every four centuries. So over long periods of time, it needed adjustments. Once again, what had been in use previously was refined and recalibrated in 1582 to become our modern-day Gregorian calendar.

November depicted in a third-century mosaic of the months in El Djem archaeological museum, Tunisia

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A 14th-century Italian miniature showing a Roman siege of a fortress. Few cities could resist Roman siege warfare

of enemy archers) and was designed to kill careless defenders on the city walls.

Another complex and fearsome weapon was the siege tower. This was a moveable wooden tower, designed to be rolled up to enemy walls, allowing the troops inside to descend onto the enemy defenders. Siege towers took time to build and needed ramps, which allowed the defenders to see what was coming and gave them time to prepare a counter-attack. Nevertheless, when siege towers were deployed, more often than not they got the Romans over the walls.

If all of these failed, a battering ram could be used against the defenders' gates. These rams were protected by a wooden gallery covered in wet cowhides to stop them being burnt by the defenders.

Once enemy walls were breached, the Roman soldiers would advance in a testudo (tortoise) formation. This involved covering their heads with their rectangular shields, with other shields protecting their front and sides. Such a formation absorbed arrows and small rocks, giving the men valuable time to get to the breach relatively unharmed.

GETTY

▼ GOVERNMENT AND ECONOMICS

Diocletian reinvented government and invented economics in a bold overhaul of Roman taxes, trade and leadership

Not all Roman experiments were successful. In AD 284, Diocletian, a man of low birth who had risen through the ranks in the army, became emperor. He solidified the idea of the 'tetrarchy': a system of sub-emperors, each one ruling over a number of provinces, all reporting to him. This meant that local issues could be dealt with locally and that power was shared (to a certain extent). Obviously a sub-emperor could go rogue, but after decades of war and strife, the tetrarchy was a welcome idea that brought peace.

By AD 300, however, Diocletian's empire was facing economic problems: free trade had broken down in some areas and prices were rising. The emperor didn't help the situation when he embarked on a costly public building programme on a scale not seen for generations.

Diocletian attempted to confront these issues head on. First, he overhauled the tax system, which eliminated ingrained inefficiencies. He also recognised that the coinage had been debased to an extent that confidence in the Roman currency had diminished, so he reminted and revalued all of the coins. While this may sound like a good idea, costs continued to rise even faster, creating a huge spike in prices. Diocletian responded by setting price caps on most resources. The penalty for disobeying these imposed price caps? Death.

The system of fixed prices was widely despised, and almost as soon as it was introduced, it was generally ignored. The law of supply and demand dictates that if someone needs something badly enough, they will pay over the odds. Under the circumstances, the black market boomed. Fortunately, the situation in AD 301 didn't last long – once the new coinage had a chance to embed itself in the Roman economy, prices began to normalise.

Diocletian was also a highly unusual Roman emperor in that, in AD 305, he voluntarily abdicated in favour of a two-emperor system. He retired to the Dalmatian coast (modern-day Croatia), where he lived out his days in splendour and spent his time cultivating cabbages.

A statue of the Tetrarchs, Diocletian's multi-leader solution to years of unrest

THE BOOK

As the first to bind written pages inside a cover, there is one thing the Romans definitely did invent: the book

After all these examples of the Romans enhancing existing ideas rather than inventing new ones, here's one that was genuinely original.

The first recognisable alphabet, and therefore writing, was developed in ancient Babylon around 3100 BC. This writing was done on clay tablets – not the most portable of formats for written literature. The Egyptians made a leap forwards with papyrus, thin sheets made from the pith of the papyrus plant.

Now knowledge could be preserved on scrolls, which were easier to transport, but still bulky. Paper itself was invented in China around the end of the first century AD, but didn't reach Europe until after the fall of the western Roman empire.

Around the same time that paper was being invented in China, the Romans invented the codex. For the first time, sheets of a uniform size were bound together along one edge, in between two larger, stronger protective covers. Now, for the first time, large amounts of written information could be concentrated in one highly transportable volume. This would become the standard way to write and store information until the digital age 1,900 years later.

Across the empire (both during and after the Roman era), the book became the standard format for writing. Most famously, the word 'bible' is a variation of the Greek word for 'the books' (*ta biblia*). The invention of the book enabled much easier sharing of complex ideas, including everything from Christianity to annals about emperors. H

Jem Duducu is the author of *The Romans in 100 Facts* (Amberley Publishing, 2015)

Science Stories
NAVIGATION

1750
Gowin Knight revolutionises the navigational compass

Gowin Knight pioneered accurate compasses with slender steel needles, like this one from c1776

Being a great inventor does not always mean having a generous nature. Gowin Knight (1713–72) won huge acclaim at the Royal Society for his magnets and compasses, but as the first director of the British Museum, he antagonised all his curators by walling up the corridor to the toilet.

Short-tempered, reclusive and mean, Knight was notoriously secretive, which contradicted the scientific ideology that research should benefit the world, not the individual. Yet reliable navigation was vital for British shipping, and the Royal Society awarded Knight its prestigious Copley Medal for his contributions to national trade and empire.

The excitement had started in 1745. "Hither to I have wrote only to blot paper," gushed an American merchant based in London, "but now I tell you some thing new Docr night a Physition has found the Art of Giveing Such a magnetic power to Steel that the poor old Loadstone is putt quite out of Countenance."

Knight was a medical student at Oxford when he first started experimenting with loadstone, a naturally occurring magnetic iron ore that varies greatly in quality and tends to lose its strength over time. Although he never revealed his precise techniques, Knight took advantage of improvements in steel manufacture to produce powerful, permanent magnetic bars.

Four years later, Knight was asked to examine a compass that had been damaged during a lightning storm at sea. Horrified to discover that its cracked casing was fastened with iron nails, and that the needle was a soft iron wire bent into a crude lozenge and taped beneath a heavy cardboard circle, Knight determined to revolutionise compass design. After extensive tests, he produced a model made of fine brass, with a slender steel needle balanced on a sharp point.

Thanks to some nifty social networking through contacts at the Royal Society, Knight managed to convince key naval officials that his expensive compasses were a worthwhile investment. Soon they were standard issue for all ships embarking on international voyages, and naval historians now celebrate him as the founder of scientific navigation.

However, technical sophistication can have drawbacks, and the initial enthusiasm soon turned to despair. As a natural philosopher researching in his London study, Knight had focused on extreme precision, and his readings were accurate to under a degree. In contrast, mariners at sea were more concerned to verify their general direction, and they complained that Knight's sensitive needle spun round and round in stormy weather. When James Cook lost his favourite but old-fashioned compass overboard, he demanded an identical replacement, rejecting newer versions because, "Doctor Knights Stearing Compas's from their quick motion are found to be of very little use on Board small Vessels at sea".

Soon Knight's compasses were standard issue for all ships embarking on international voyages

In retrospect, Knight's most significant achievement was to build a scientific career. An adept social climber, he started low and finished high, succeeding because he knew how to market himself and the instruments he produced.

Knight is an outstanding example of those Enlightenment experimental entrepreneurs who, fired by hardship as well as enthusiasm, supported themselves through teaching, writing, inventing and lecturing. Collectively, they made science respectable. At the beginning of the 18th century, natural philosophers and inventors were figures of fun, mocked as bumbling virtuosi and impractical projectors. A hundred years later, no young man or woman could call themselves educated unless they knew some science. H

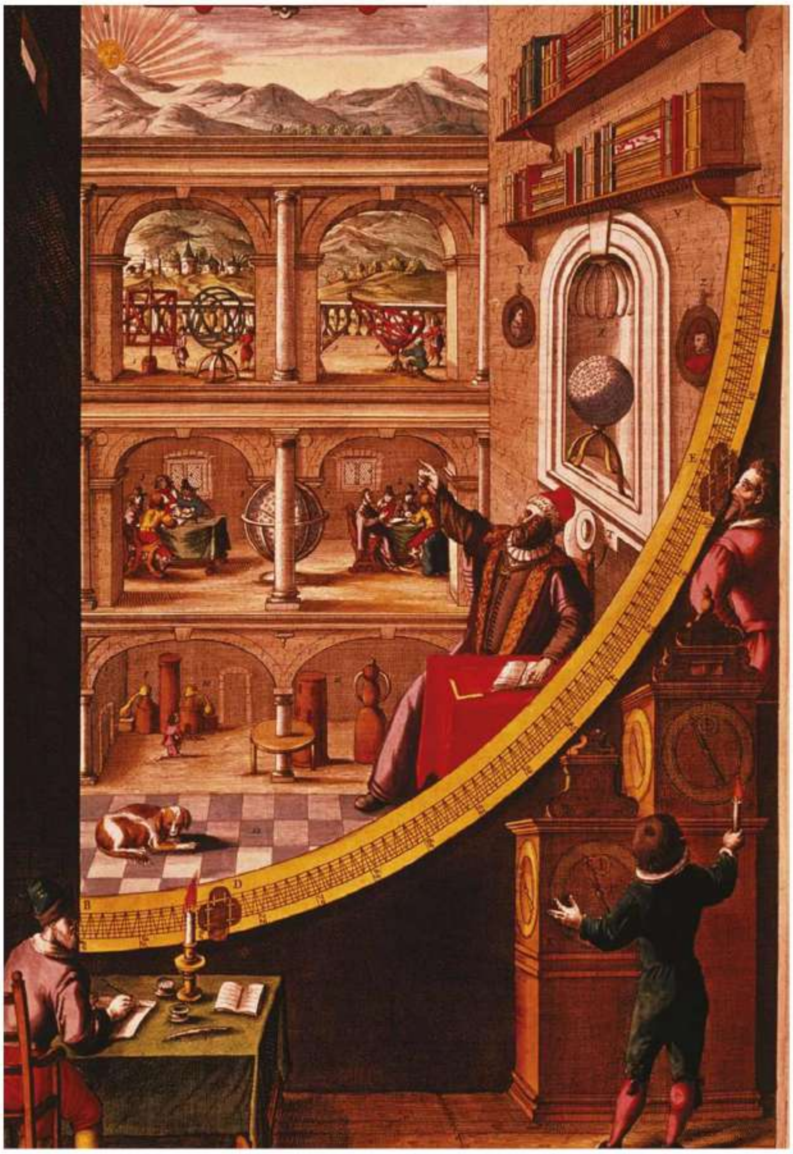
Words: Patricia Fara

A HISTORY OF SCIENCE IN 10½ OBJECTS

Joseph Wright's 1768 painting, *An Experiment on a Bird in the Air Pump*, shows a travelling lecturer demonstrating Robert Boyle's famous vacuum-creating instrument to a (mostly) captivated audience

From the early calculator that helped merchants do complex sums in seconds to the x-ray that unlocked the secrets of DNA, **Patricia Fara** introduces objects that have transformed our understanding of the world (and universe) over the past 500 years

ALAMY



Tycho Brahe surveys the heavens in his mural quadrant, as depicted in the frontispiece to *Astronomiae Instauratiae Mechanica* (1598)

1 TYCHO BRAHE'S MURAL QUADRANT

The brass quarter-arc that helped an unorthodox Danish astronomer compile the world's most accurate set of star data

Tycho Brahe (1546–1601) was no ordinary 16th-century astronomer. Following an unfortunate duel he wore an artificial nose, and he supposedly died from a burst bladder at a feast.

More importantly, Tycho rejected conventional academic career routes, eventually acquiring royal funding for a massive observatory on the island of Hven, which is now a Danish heritage site on Swedish territory. He was particularly proud of his giant quadrant, the brass quarter-arc astronomical device around two metres in height that can be seen in the frontispiece illustration above.

Most of this picture is itself of a picture – Tycho and his snoozing dog belong to a mural painted within the quadrant device, which is fixed to the wall and used to measure the precise position of a star as it passes by the small sight on the top left. Behind the virtual Tycho's outstretched arm lie illustrations of his observatory's three floors: the roof top for making night-time observations, the library with its immense celestial globe, and the basement devoted to carrying out experiments. An observer is just visible on the right, calling out to his assistants who coordinate their measurements of a moving star's time and position.

Tycho compiled the world's most accurate and comprehensive set of star data. And, although Tycho believed the Sun revolves about us, Galileo used his observations to confirm that the Earth indeed moves.

2 JOHANNES KEPLER'S MODEL OF THE UNIVERSE

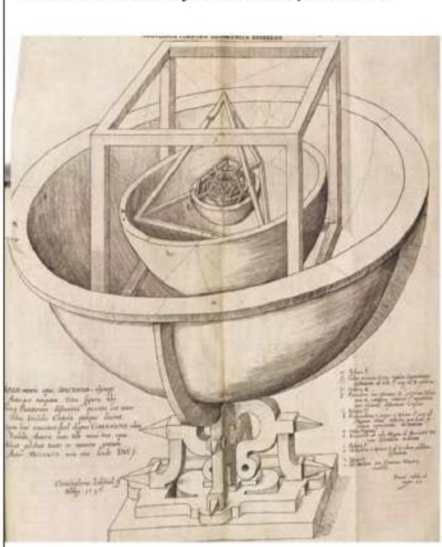
The harmonious musical cosmos imagined by the astronomer famous for showing that planets move in ellipses

In 1600, an impoverished astrologer and former university teacher called Johannes Kepler (1571–1630) found refuge in the imperial court at Prague. While his three laws describing how the planets move still lie at the heart of Newtonian astronomy, Kepler himself believed in a magnetic musical universe structured to mirror God's perfect geometrical forms.

In Kepler's harmonious vision, which he illustrated by drawing an imaginary cosmic model, God had spaced out the planetary spheres so that symmetrical shapes could be nested between them. The outermost orbit of Saturn is separated from its neighbour – Jupiter – by a cube. Moving inwards, a pyramid lies between Jupiter and Mars. Similarly, other solids frame the paths of Earth, Venus and Mercury around the Sun.

Kepler decided that the Sun must affect the motion of the planets, and he started by tackling the astrological God of War, Mars. This planet's orbit clearly deviated from circular perfection, and after many tortuous calculations and blind alleys, Kepler showed that the orbit of Mars is an ellipse.

Yet what might now seem like a great scientific leap forward was ignored for decades. It was only in 1631, after Kepler had died, that his elliptical model was vindicated, when Mercury passed in front of the Sun exactly as he had predicted.



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Kepler's imaginary cosmic model shown in *Mysterium Cosmographicum* (1596)

3 JOHN NAPIER'S BONES

The early calculator that made sums quick and easy

Have you ever wondered how the Romans did multiplication? Even the two-times table expands into nightmarish proportions if you try to work it out in Latin numerals. Hardly surprising, then, that when Hindu-Arabic numbers were imported into Europe at the beginning of the 13th century, merchants and mathematicians enthusiastically adopted the new system of nine digits plus zero that we still use.

Even so, when dealing with large numbers, it was easy to make mistakes. Division posed still more of a problem, to say nothing of square roots.

Four centuries later, the Laird of Merchistoun – better known as Scottish mathematician John Napier (1550–1617) – decided it was time to make routine arithmetical tasks easier. He invented a special type of abacus, a set of rotating rods each inscribed many times over with the ten basic digits. Soon known as Napier's bones (expensive ones were made of bone or ivory), this device made it possible to carry out long calculations quickly and accurately. You just line up the rods and read off the answer.

A set of John Napier's 'bones', which made arithmetic a little less nightmarish in the 17th century

4 ROBERT BOYLE'S AIR PUMP

The device that produced a completely artificial state: a vacuum

Britain's most famous scientific picture (see page 25), by Joseph Wright of Derby, shows a red-robed philosopher lecturing about an air pump to a small family group, his hand poised on the stop-cock that will determine the life or death of a white bird inside the glass globe.

Developed a hundred years earlier by Robert Boyle (1627–91) and Robert Hooke (1635–1703), the air pump was a completely new type of instrument because it produced an artificial state – a vacuum. By turning the crank at the bottom, an experimenter could mechanically suck most of the air out of a glass globe. Critics may have denied that anything valid could be learnt about reality from a situation that was non-existent in nature, but the experiments were convincing. Moving bells inside the evacuated sphere could be seen but not heard, flames were extinguished and rabbits died.

By the time that Wright was painting, the air pump had become an emblem of modern technology. His group portrait displays the mixed reactions still evoked by scientific research – wonder, absorption, terror – and also the complete lack of interest manifested by the couple on the left, who have eyes for nobody but each other.

GETTY

We can never know whether Newton's apple really did fall, but **its impact has been enormous**

5 ISAAC NEWTON'S APPLE

The fruit that may or may not have fallen from a tree and inspired Newton's theory of gravitation

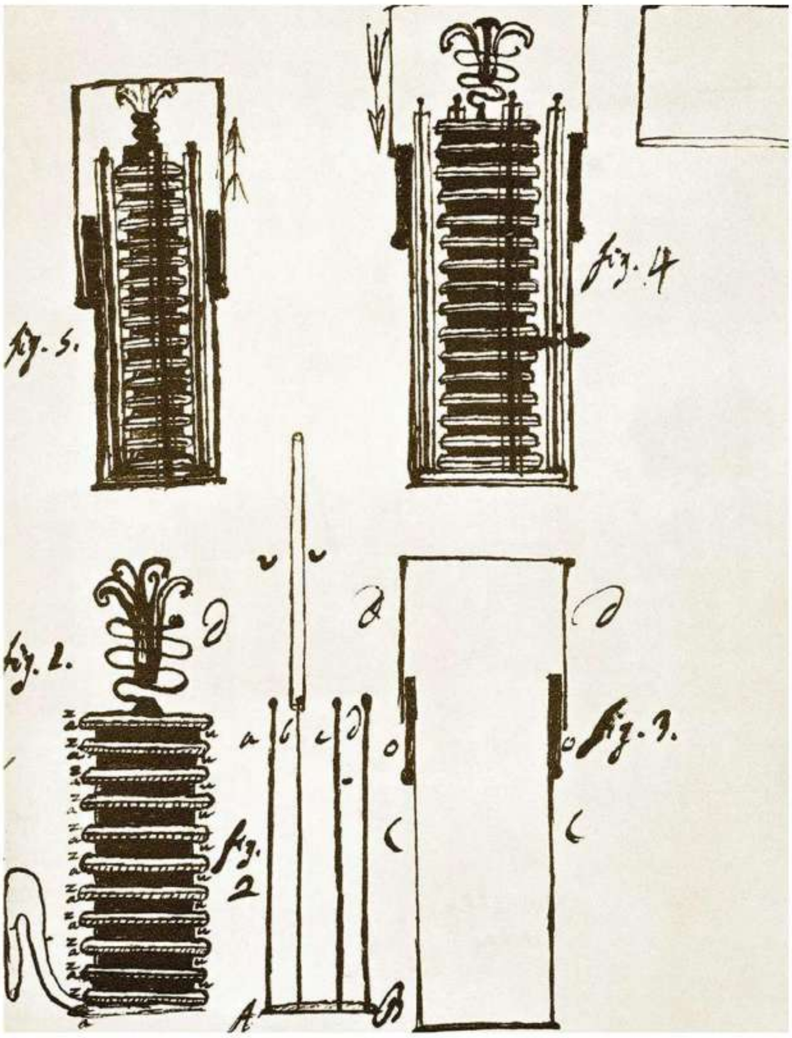
Most people know only one thing about Isaac Newton (1642–1727): that he watched an apple fall from a tree. Rather like St Catherine's wheel or St Jerome's lion, Newton's apple has become an iconic attribute of scientific genius.

The story originated with Newton himself, who as an elderly man reminisced about a day nearly 60 years earlier when "he sat in a contemplative mood. Why should that apple always descend perpendicularly to the ground, thought he to him self. Why should it not go sideways or upwards, but constantly to the earths centre? Assuredly, the reason is, that the earth draws it..."

For Newton and his contemporaries, this episode resonated symbolically with the Fall in the Garden of Eden, when Eve persuaded Adam to bite into the forbidden fruit from the tree of knowledge.

After a long absence, the apple reappeared in the 19th century and soon acquired mythological significance. When Oxford University built its Gothic-style museum for teaching science, stone statues were installed to inspire students. Newton was among the first six, gazing down at his apple as though it had fallen from heaven. We can never know whether that apple really did fall, but its impact has been enormous.

Isaac Newton contemplates a fallen apple in this statue at Oxford University Museum



Alessandro Volta's drawing of the world's first electric battery (1800)

6 VOLTA'S PILE

The prototype battery that its inventor perfected by giving himself electric shocks

Alessandro Volta (1745–1827) was a sharp operator. Based in Italy, he consolidated his international reputation by cultivating scientific friendships all over Europe and pledging his allegiance to Napoleon. In 1800, he chose British journals for launching his revolutionary instrument that provided a new source of power – current electricity.

To make this prototype battery, Volta piled up discs on vertical glass rods, alternating two different metals and separating them with cardboard soaked in salty water. Incorporating himself as an experimental subject, Volta placed one hand in the basin of water at the bottom, and the other on the metal plate at the top. Sometimes he even used his tongue as a detector. The shocks he received were, he claimed, proof that animal electricity – the kind already observed in electric eels or twitching frogs' legs – was identical to artificial electricity produced in a laboratory.

Volta was as interested in defeating his rivals – especially his fellow Italian Luigi Galvani – as in providing solid evidence. His article was a rhetorical masterpiece, convincing his readers by describing his results at length yet managing to avoid the awkward questions.

Volta was **as interested in defeating his rivals** as in providing solid evidence

7 CROOKES' TUBE

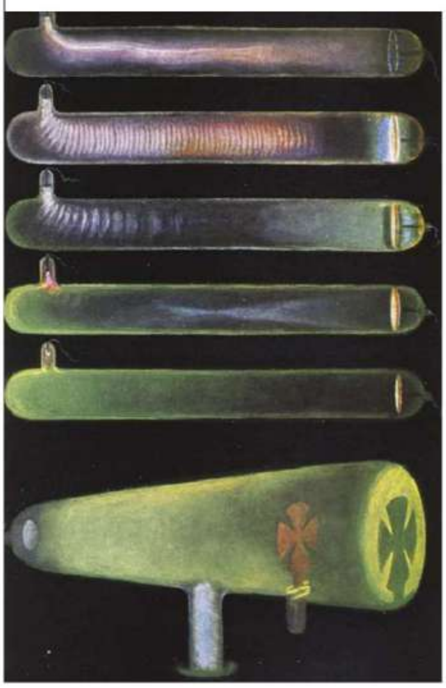
The mysterious glowing apparatus in which electrons were discovered

It's the 1870s. Imagine the bewilderment of scientists gazing at this glowing electric tube. Inside, it contains only gas at a very low pressure, so what could be producing that eerie green luminosity? The strong shadow of a Maltese cross suggests that this is an optical phenomenon, but another experiment shows that something – but what? – is strong enough to push a little cart along some miniature rails. Could it be a stream of particles, or perhaps some mysterious rays?

This apparatus was developed by William Crookes (1832–1919), an ingenious British physicist who created movement and shadows to back up his claims that a strange substance is being emitted by one of the electric plates in his tube. Crookes suggested that spiritualism may be behind the effect, and after several prominent mediums survived his rigorous tests without being caught cheating, some eminent scientists believed that it really was possible to contact the dead.

Sceptics accused them of being duped by charlatans, but Crookes suggested that radio might have a human analogy, so that people with especially sensitive organs can tune in to vibrations carried through space. Crookes's evidence was persuasive, and he was partially vindicated when his rays were shown to be electrons. His séance experiences have never been fully explained.

Crookes' tube led some scientists to believe that it's possible to contact the dead



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The 100-inch Hooker telescope at the Mount Wilson Observatory used by Hubble to calculate galaxy distances and prove the expansion of the universe

9 EDWIN HUBBLE'S TELESCOPE

The instrument that helped a First World War veteran establish that the universe is expanding

Not many people could make Albert Einstein admit he had made a mistake, but Edwin Hubble (1889–1953) was one of them. After serving as a soldier in the First World War – his lab nickname was 'The Major' – Hubble went to the Mount Wilson Observatory in California, where he used the world's largest telescope to discover nebulae lying far beyond our own galaxy.

To measure the cosmos, Hubble needed an astronomical ruler, and he borrowed one invented by Henrietta Leavitt, a mathematical drudge or human computer based at Harvard. Like countless other intelligent women in this pre-electronic era, she was sufficiently desperate for work to tolerate long hours and low wages, and through tedious calculations she showed how flashing stars can be used to estimate stellar distances.

Thanks to Leavitt, Hubble produced his own graph proving that the further away a galaxy is, the faster it is racing away from the Earth. This diagram confirmed a consequence of relativity theory that Einstein had previously refused to accept – that the universe started out as a small dense cluster and has been expanding ever since. Although Einstein was converted, other scientists disagreed; ironically, the expression 'big bang' was coined by one of the theory's most outspoken opponents.

8 MRS RÖNTGEN'S RING

The jewel in the crown of the world's first X-ray image

Academic articles rarely mention scientists' families, but this photograph suggests that 19th-century wives may often have been involved in research projects.

When Wilhelm Röntgen (1845–1923) stumbled across a mysterious type of radiation, he was a conscientious German professor methodically repeating some earlier experiments. While checking his apparatus to make sure it was light-proof, he noticed a strange shimmering some distance away. Röntgen then set about a systematic investigation, eating and sleeping in his laboratory for several weeks.

A fortnight after his initial discovery, he asked his wife, Anna Bertha, to hold her hand in the path of the rays that he labelled X to indicate his bafflement. "I have seen my death," she exclaimed prophetically when she was shown her bones with their ghostly coating of flesh. She was right – this weightless, electrically neutral radiation would often prove fatal. Yet within a few years, X-rays had entered the repertoire of fairground performers. As one magazine wrote: "I'm full of daze; Shock and amaze; For now-a-days; I hear they'll gaze; Thru' cloak and gown – and even stays; These naughty, naughty Röntgen Rays."

Anna Bertha Röntgen's ringed hand captured in the world's first X-ray photograph, in 1895. Bertha's husband, Wilhelm, won a Nobel Prize in 1901 for his research

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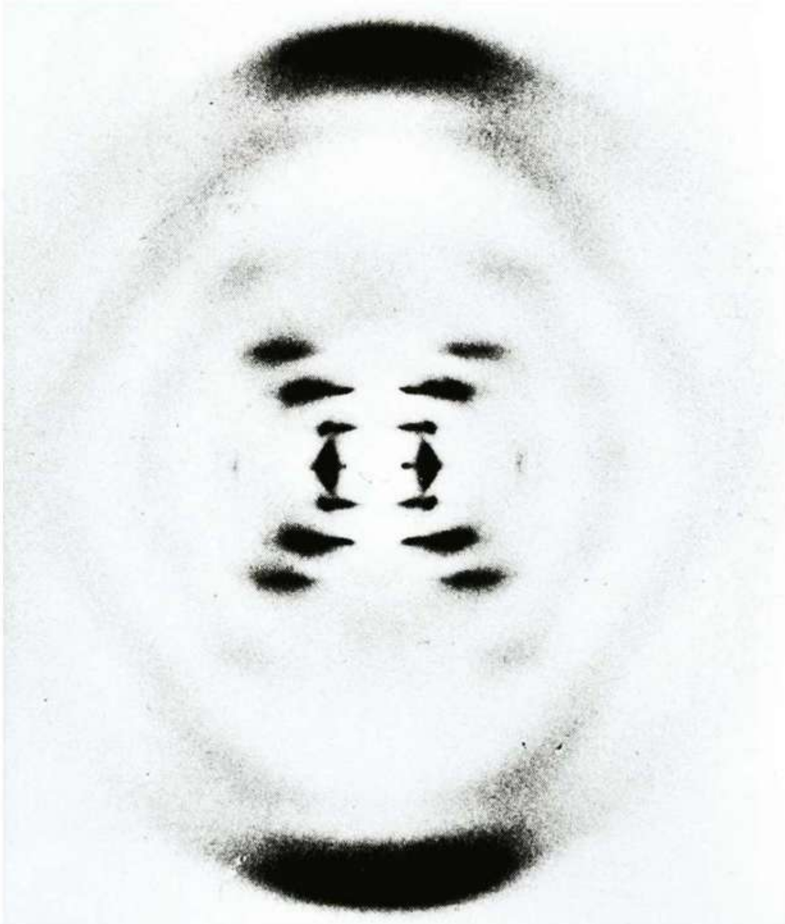

10 ROSALIND FRANKLIN'S X-RAY PHOTOGRAPH

This image, taken in a London laboratory in the early 1950s, was crucial in unlocking the secrets of DNA

When the crystallographer Rosalind Franklin (1920–58) produced the x-ray photograph above in London in the early 1950s, she carefully filed it away for future analysis. A firm believer in following scientific protocol, she had been trained to carry out her research methodically, and she was determined to complete her current set of experiments before exploring any further possibilities, however tantalising they might seem.

James Watson (1928–) was a very different character. A young American PhD student at Cambridge, he was impulsive, ambitious and firmly focused on his goal: to decipher the structure of DNA. Watson defied his boss's instructions to get on with his own work, and instead engaged in clandestine meetings with Francis Crick (1916–2004) as they struggled to solve science's biggest puzzle.

When Watson was shown Franklin's picture without her knowledge, he immediately recognised its significance – "my mouth fell open and my pulse began to race," he reported in his bestselling book, *The Double Helix*. Although not an expert like Franklin, Watson knew that the prominent X shape revealed a spiral, and he realised later that two molecular strands must be intertwined. Fully analysing the photograph involved careful measurements and long calculations. Both Watson and Crick soon rushed into print, claiming that by unravelling the structure of complex molecules inside genes, they had discovered the secrets of inheritance. Franklin died young, in 1958, but her contribution to the understanding of DNA is now fully recognised.

Watson engaged in clandestine meetings with Crick as they **struggled to solve science's biggest puzzle**

It wasn't until the invention of the laser in 1960 that 3D holography could develop

10½ THE HOLOGRAM

The 3D image that made a 15-year journey from half-realised theory to practice

Impossible to pin down with a photograph, holograms flicker from one half-state of existence to another. Unlike almost every other scientific invention, the theory underpinning holograms was thoroughly worked out long before the first one was created.

Dennis Gabor (1900–1971), a Hungarian Jew who had fled to Britain, developed the idea in 1947. Using standard laws of optical physics, he suggested that the 3D-appearance of an object might be recorded permanently, to be made visible once again by shining the same type of light as before. For years, holograms existed in a limbo state, envisaged intellectually but unrealised in practice. It was only after lasers were invented in 1960 that holography became feasible. H

Patricia Fara is president of the British Society for the History of Science

DISCOVER MORE

BOOK

▶ **Science: A Four Thousand Year History** by Patricia Fara (OUP, 2009)

WEBSITE

▶ For more information on **key objects in the history of science**, log on to the website of the Whipple Museum of the History of Science: *hps.cam.ac.uk/whipple/explore*

10 GLOBAL MILESTONES

IN THE HISTORY OF SCIENCE AND TECHNOLOGY

From Babylonian mathematics to Inuit climate science, **James Poskett** picks ten of the most remarkable stories from the global history of science and technology

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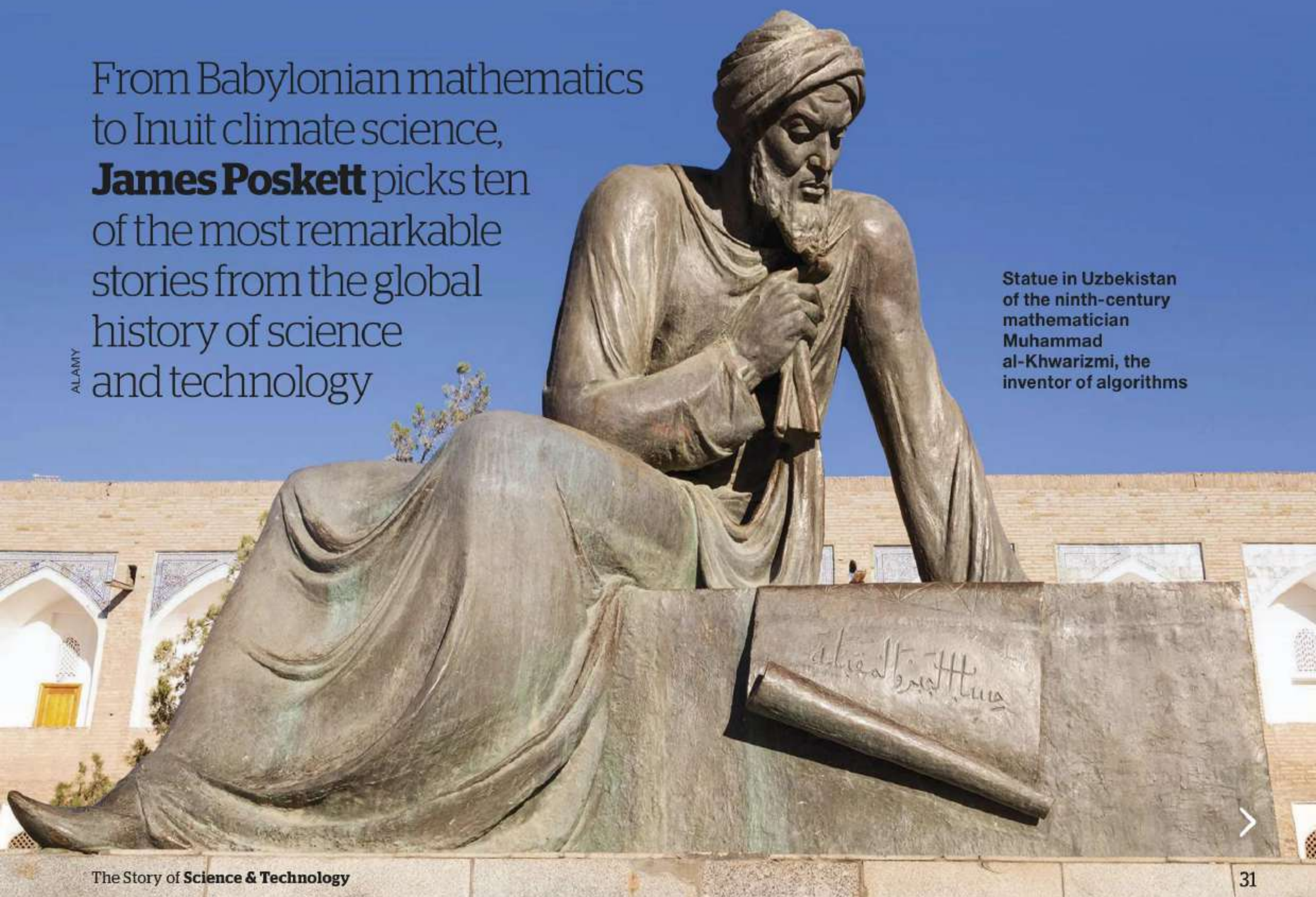


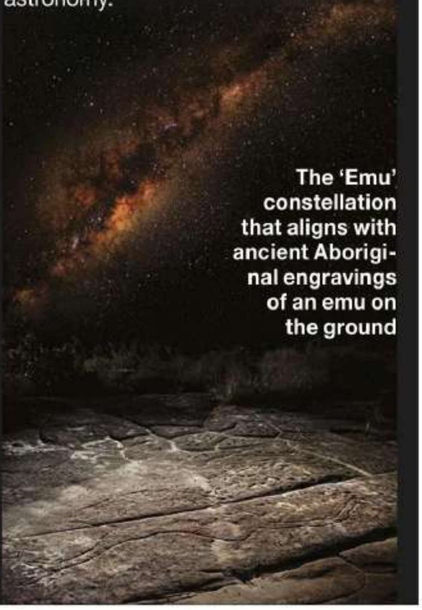
Statue in Uzbekistan of the ninth-century mathematician Muhammad al-Khwarizmi, the inventor of algorithms

▼ ABORIGINAL ASTRONOMY

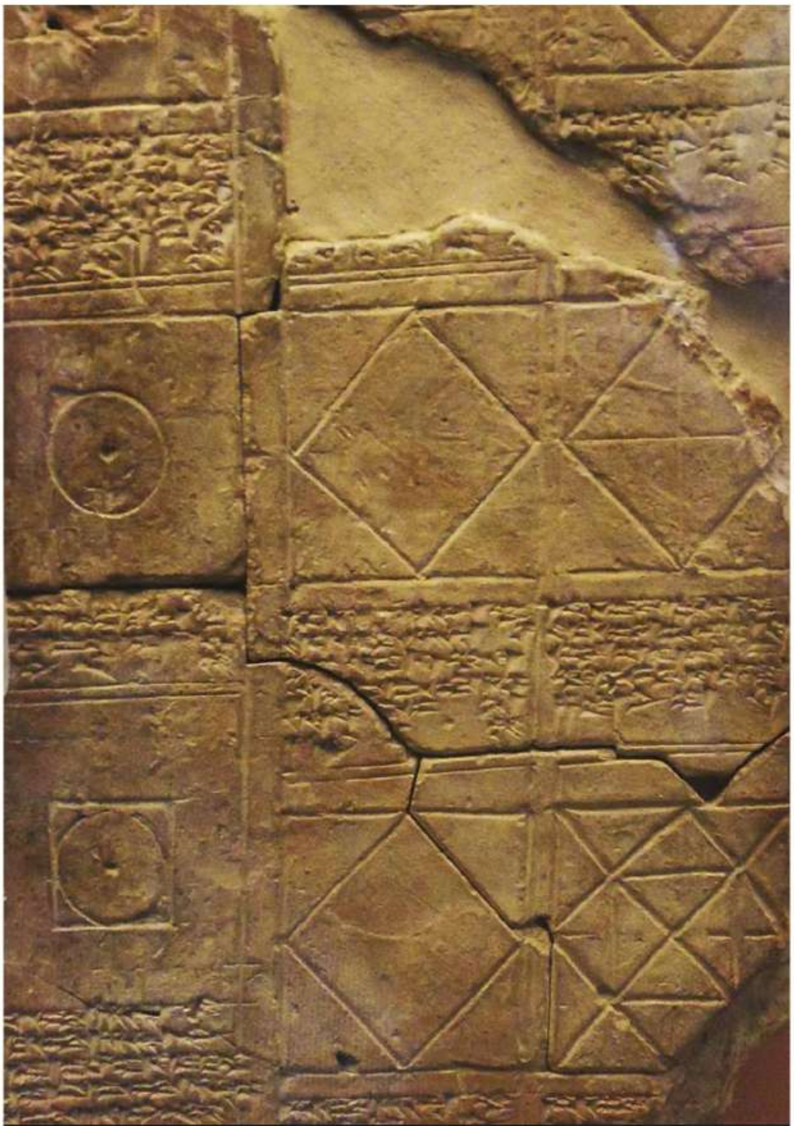
Australia's indigenous people can lay claim to being the world's oldest astronomers

Aboriginal Australians were among the world's first astronomers. For at least 10,000 years, astronomy has been a fundamental part of Aboriginal culture. By identifying different stars and constellations, Aboriginal people have linked the heavens to major life events. The Kamilaroi people hold male initiation ceremonies with the setting of Djulpan – a constellation representing a hunter in a canoe. What makes this all the more intriguing is that Djulpan actually corresponds to the European constellation known as Orion, also a hunter. (Although in the southern hemisphere Orion is upside down!)

Astronomy also serves a range of more practical functions for Aboriginal Australians. The seafaring Yolngu people track the position and phase of the moon in order to predict the height of the tide. Similarly, the Wardaman people of northern Australia are able to navigate across the desert at night, simply by following the stars. Today, this ancient astronomical knowledge can still be found in rock engravings across Australia. Just to the north of Sydney, in the Ku-ring-gai Chase National Park, you can find a series of incredible engravings made by the Kuringgai people. Perhaps over 4,000 years old, one of these represents the 'Emu' constellation. And on a clear autumn night, the engraving aligns perfectly with the stars in the sky, an archaeological testament to Aboriginal Australian astronomy.



The 'Emu' constellation that aligns with ancient Aboriginal engravings of an emu on the ground



Cuneiform script and illustrations on a Babylonian tablet show a set of problems relating to calculating volume, together with the solutions

▲ BABYLONIAN MATHEMATICS

An advanced Mesopotamian numbers system that we still use 4,000 years later

Ever wondered why there are 60 seconds in a minute? Or 360 degrees in a circle? The answer lies in ancient Babylon (modern day Iraq). Today, the majority of mathematics is done in what is known as base ten. You learn at school that there are units, tens, hundreds and thousands. This makes things pretty easy for counting on your fingers. But nearly 4,000 years ago, the people of ancient Babylon used base 60, which divides each unit into 60 parts. The easiest way to understand this is to think of time: we have 60 seconds in a minute and then 60 minutes in an hour. (To be really consistent in base 60, we should then have 60 hours in a day and 60 days in a month!).

Historians and archaeologists have deciphered clay tablets, some dating to 1800 BC, which show that ancient Babylonian people did really complex mathematics in base 60. Many of these tablets relate to the administration of the Babylonian empire, calculating interest on loans or the size of land plots. But there is also evidence that Babylonian mathematicians developed geometrical theorems well before the Greeks. The ancient people of Iraq knew Pythagoras's theorem before Pythagoras himself.

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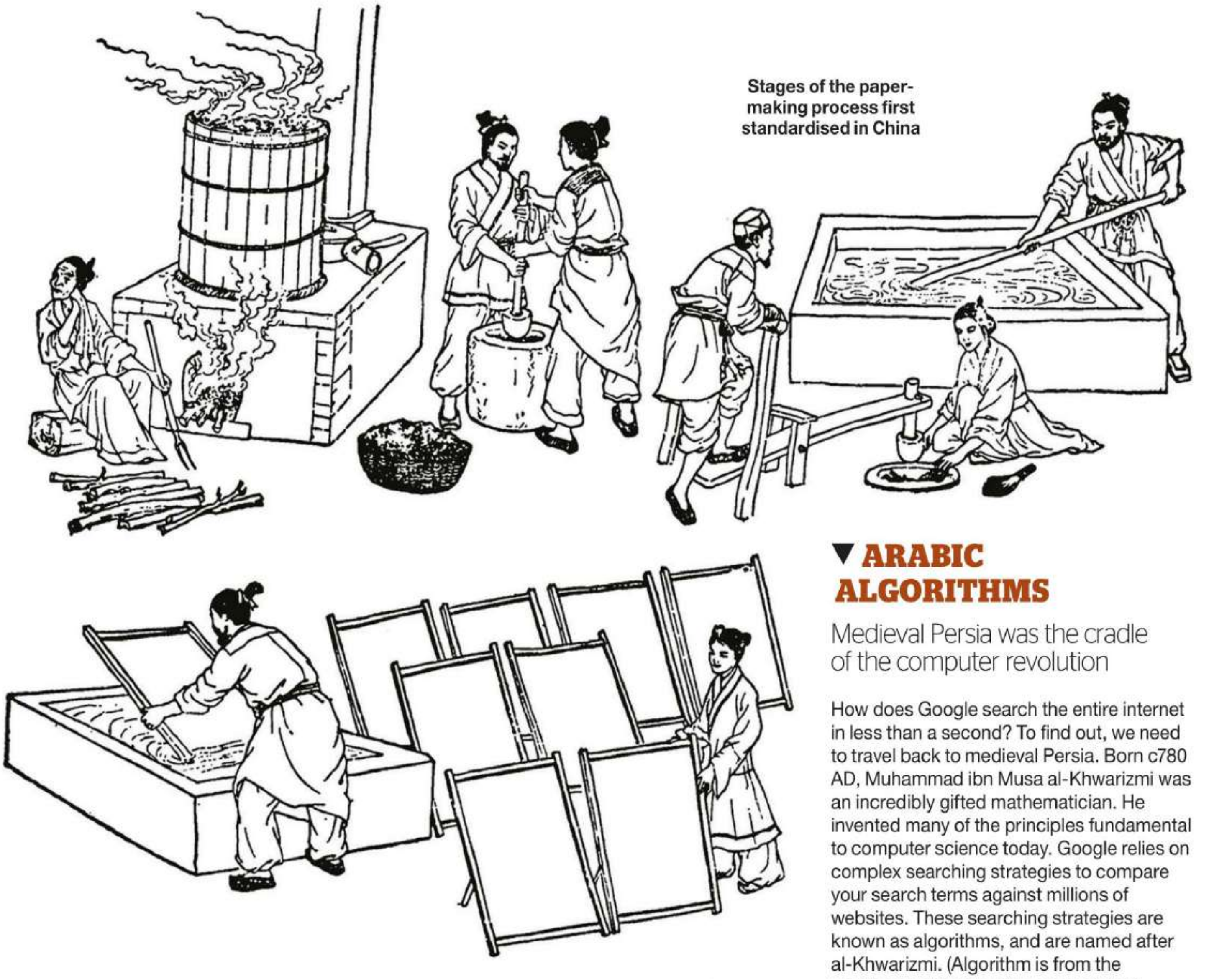


Stages of the paper-making process first standardised in China

▲ CHINESE PAPER

A eunuch brought the benefits of paper to China, but it took centuries for the world to catch up

This special edition you're reading relies on an ancient Chinese technology: paper. It might sound a bit mundane, but the invention of paper really did change the world. Before that, human societies had been writing on papyrus, parchment and clay tablets. These all had their drawbacks. The papyrus used in ancient Egypt was relatively cheap but tended to rot. The parchment used in Rome was strong but expensive as it was made from animal skins. And the clay tablets used in ancient Babylon were both difficult to store and easy to break. Paper solved all of these problems. It was strong and durable, easy to store in a library and, most importantly, it could be printed on.

The oldest surviving fragments of paper date to the second century BC. But Chinese papermaking really took off in the second century AD, when the Chinese eunuch Cai Lun presented a sample of paper to the Han emperor. The emperor was so impressed that he made Cai Lun swear to keep paper a secret. For centuries, Europeans tried to learn how to make paper. Some even resorted to kidnapping and interrogating paper manufacturers. And so, while it might seem unremarkable today, paper was a Chinese invention that people fought over and even died for.

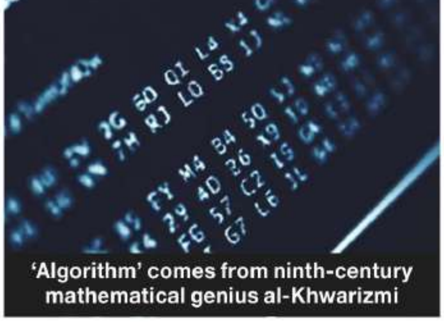
The emperor was so impressed that he made Cai Lun **swear to keep paper a secret**

▼ ARABIC ALGORITHMS

Medieval Persia was the cradle of the computer revolution

How does Google search the entire internet in less than a second? To find out, we need to travel back to medieval Persia. Born c780 AD, Muhammad ibn Musa al-Khwarizmi was an incredibly gifted mathematician. He invented many of the principles fundamental to computer science today. Google relies on complex searching strategies to compare your search terms against millions of websites. These searching strategies are known as algorithms, and are named after al-Khwarizmi. (Algorithm is from the medieval Latin *algorismus*, a mangled transliteration of al-Khwarizmi's name.)

This wasn't al-Khwarizmi's only contribution to science and mathematics. He also invented a system of notation for balancing mathematical equations. Today we call this algebra, from the Arabic word meaning 'the reunion of broken parts'. In fact, you might have noticed that lots of scientific terms start with 'al'. As well as algorithm and algebra we've got alkali and alchemy. Well, 'al' is the Arabic definite article – the equivalent of the English word 'the'. The Middle East was really at the heart of science in the medieval period. It was through translations of scholars working in Arabic that Europeans learned new ways of doing mathematics, chemistry and astronomy.



'Algorithm' comes from ninth-century mathematical genius al-Khwarizmi

AKG IMAGES/DREAMSTIME

Jai Singh II's vast Jantar Mantar buildings, used to accurately predict astronomical events

▲ INDIAN ENLIGHTENMENT

The 18th-century search for enlightenment spreads east thanks to a far-sighted king

One of the most accurate scientific instruments of the 18th century was built in India. The Maharajah Jai Singh II was a keen astronomer. And in Jaipur he built the Jantar Mantar, a series of enormous stone astronomical instruments, completed in 1734. The largest of these, the Vrihat Samrat Yantra, can measure local time to the nearest two seconds. At 27m tall, it is still the world's largest sundial. The other instruments which make up the Jantar Mantar allowed Jai Singh to calculate and publish detailed astronomical tables, predicting the movement of planets and stars. Another instrument, the Chakra Yantra, gave Jai Singh the local time at different observatories around the world.

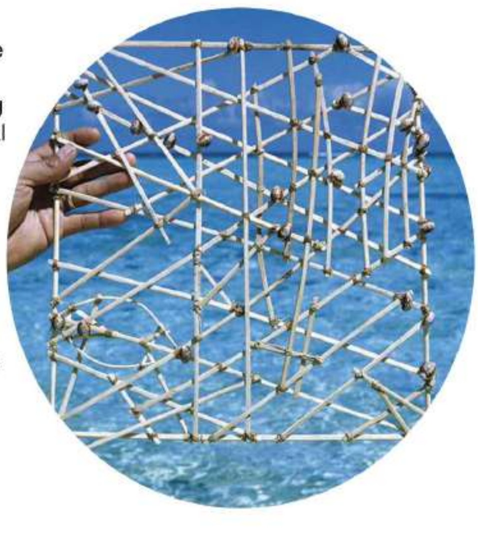
This, after all, was an age in which mathematical and astronomical knowledge was exchanged across cultures. Jai Singh wanted to know about astronomy in London, and to compare his own tables of measurements with those published in Paris. In Jaipur, Jai Singh read the latest French astronomical books brought over by Jesuit missionaries. Later in the century, in Calcutta, the astronomer Tafazzul Husain Khan translated Isaac Newton's masterpiece, *Principia Mathematica*, into Arabic. The laws of motion, like Enlightenment science more generally, reached far beyond Newton's study in Cambridge.

▼ PACIFIC NAVIGATORS

With basic materials and centuries-old techniques, Pacific islanders successfully mapped their vast ocean world

When Captain Cook travelled to the Pacific in the 1760s, he took with him the most advanced navigational instruments the Royal Navy could supply. Carefully plotting each stage of their journey, Cook and his crew used clocks and telescopes to find their way to Tahiti and on to New Zealand. The Pacific Ocean is so vast, with little land to guide navigation, that few Europeans had contemplated crossing it until the Enlightenment age of scientific exploration. But for hundreds of years before Cook's arrival, the indigenous people of the Pacific had been navigating this enormous ocean. They did so using their own sophisticated navigational technologies. Among these were sea charts made from shells and sticks collected on the beach.

Rather than a map of the land and water, these charts gave navigators a picture of the wind and currents, with individual islands marked by shells. This proved much more effective for navigating such a vast ocean. When Cook arrived in Tahiti in 1769, he was amazed to find a local man named Tupaia who was able to draw an incredibly accurate map of the surrounding islands. By following Tupaia's map of the wind and currents, Cook's voyages relied on both Pacific and European navigational tools.



Sticks and shells denote wave patterns and islands in this chart made by Marshall Islanders

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▼ AFRICA'S BOTANICAL LEGACY

A rare credit given to a botanist slave attests to the part Africans played in science's expansion

Quassia amara is a beautiful pink flowering shrub native to South America. Most plants are named after the famous European men who discovered them. But this one is named after an enslaved African – Graman Quassi. It's a reminder of the important role that African people played in the development of botany. At the beginning of the 18th century, Quassi was captured in Ghana and forcibly transported to Surinam, a Dutch colony in South America. Working on the plantations, he got to know the local plant life well. Soon enough, he was using extracts from this incredible pink shrub, also known as 'bitter-wood', to cure fevers and gut parasites.

When the Swedish botanist Carl Linnaeus heard about all this, he was so impressed that he named the plant *Quassia amara* after the Ghanaian. Quassi's story is inspiring, but most Africans did not receive this kind of recognition. Yet they too helped European botanists understand the plant life of the New World. From maize and yams to peas and chocolate, European botanists relied on African knowledge to cultivate and study tropical plant life in the 18th century.

***Quassia amara*, named in honour of Graman Quassi's knowledge of the bitter wood's medicinal properties**

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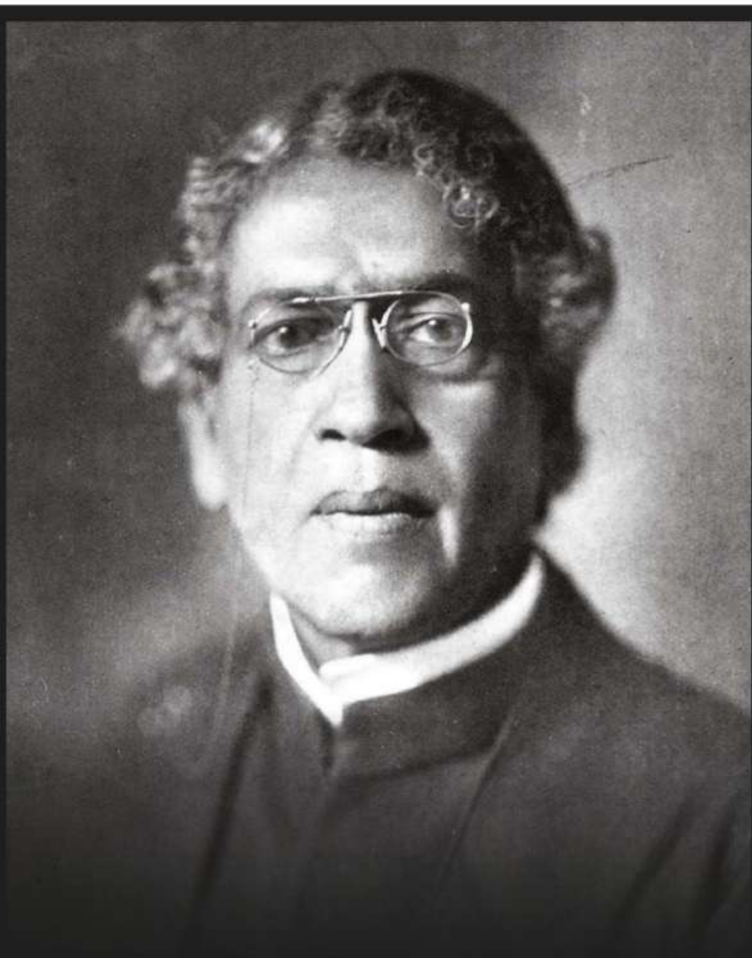


Renaissance man Jagadish Bose made major discoveries in biophysics as well as his world-changing work in radio and microwave sciences

▲ INDIAN AIRWAVES

A polymath and pioneer in microwave optics technology, the Indian who heralded an age of mass communication

At midnight on 15 August 1947, the first prime minister of independent India addressed the new nation. Jawaharlal Nehru famously declared: "At the stroke of the midnight hour, when the world sleeps, India will awake to life and freedom." Nehru's 'Tryst with Destiny' speech is considered one of the greatest of the 20th century. Millions of people listened as the new prime minister's words were transmitted across the airwaves to radios in India and beyond. In using the radio, Nehru was relying on the work of one of his countrymen born nearly 100 years earlier.

Jagadish Chandra Bose (1858–1937) was the definition of a polymath. Born in 1858 in the Bengal Presidency of British India, Bose studied mathematics, plant physiology, biophysics and archaeology. He even wrote Bengali science fiction at the same time as HG Wells was pioneering the genre in English. But Bose is most celebrated for his contribution to the study of radio and micro-waves. Through a series of experiments made in Calcutta, Bose proved that electromagnetic waves existed at lengths of just five millimetres. He was also the first to use a semi-conductor to detect electromagnetic waves, now a standard part of any radio or computer circuit.

Millions of people listened as the new prime minister's words were **transmitted across the airwaves to radios in India and beyond**

Wrangling 2,500 characters, typewriters eventually transformed office work, as well as the mass production of pamphlets, in Communist China

▲ THE CHINESE TYPEWRITER

Pioneering predictive text long before mobile phones, Chinese engineers solved a wordy problem

How do you make a typewriter for a language with over 50,000 characters? This was the problem facing Chinese engineers in the early 20th century. At first, the solution seemed to lie in being selective. Although there are over 50,000 characters in Modern Standard Chinese, you can read a newspaper with knowledge of about 3,000. With this in mind, the first Chinese typewriter, developed in Shanghai in the 1910s, featured just 2,500 characters. Better, but still a lot more than could fit on a keyboard. And so the Chinese typewriter featured a flat tray in which all 2,500 metal characters sat.

The typist then moved a lever over the tray, placing it above the exact character they wanted before pressing a button. This unfortunately proved incredibly slow. Chinese typists could only manage about 20 words per minute, whereas a professional secretary could reach 60 words per minute in English. This problem was ultimately solved by the invention of a kind of predictive text. In the 1950s, Chinese engineers realised they could massively increase the rate of typing by reorganising the characters on the tray.

Instead of arranging the characters like a dictionary, Chinese engineers grouped characters together which usually followed one another. With Communism on the rise, the character for 'socialism' (shehui zhuyi) was placed next to 'politics' (zhengzhi) and 'revolution' (geming).

Instead of arranging the characters like a dictionary, **Chinese engineers grouped characters together which usually followed one another**

▼ INUIT CLIMATE SCIENCE

Insights passed on through the generations provide ancient perspectives on modern climate change

Few understand the impact of climate change better than the Inuit people of the Arctic. For generations, the Inuit have closely studied their environment. Many tribes migrate to new hunting grounds with the change of the seasons, following long-established routes through the snow. The ice is part of their life. As a consequence, Inuit oral histories provide some of the most detailed documentary evidence we have of climate change, often stretching back hundreds of years. Many Inuit recall how their parents and grandparents used to cross rivers that are now dried up.

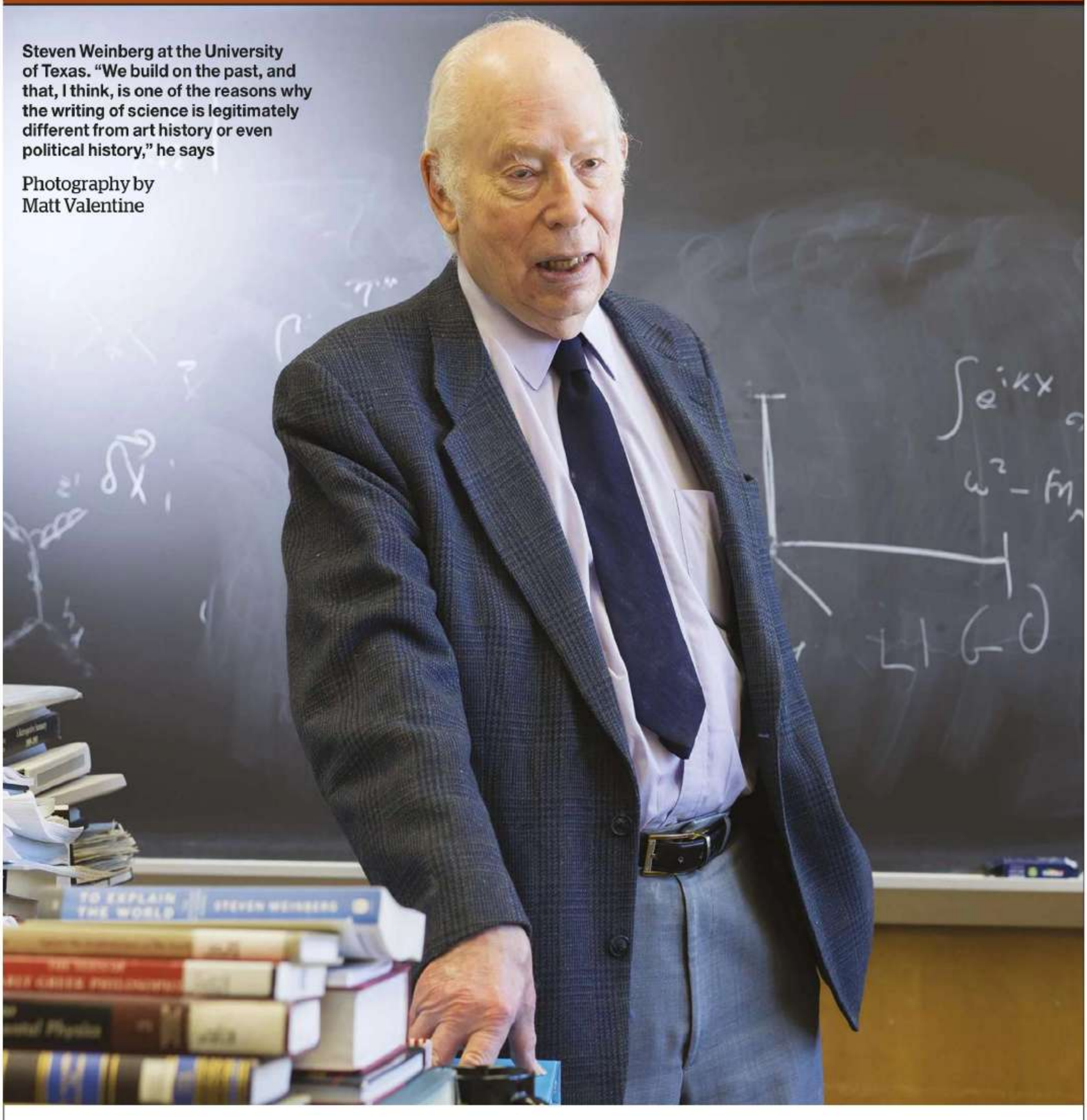
Today, the Inuit continue to play an important role in the development of climate science. The Nunavut Climate Change Centre in Canada hosts research projects to which local people contribute. Inuit elders were recently asked to tell the history of the changing landscape in Nunavut. These historical accounts were then compared to the permafrost samples collected by scientists, helping to confirm the pattern of environmental change. In Inuit traditions, changes in the environment are often attributed to human actions. Fittingly, scientists today are using Inuit evidence to convince the rest of the world that climate change is exactly that: man-made. H

Climate scientists are tapping into knowledge developed by the Inuit inhabitants of Nunavut over millennia

James Poskett is assistant professor in the history of science and technology at the University of Warwick

BOOKS / HISTORY OF SCIENCE

INTERVIEW



Steven Weinberg at the University of Texas. "We build on the past, and that, I think, is one of the reasons why the writing of science is legitimately different from art history or even political history," he says

Photography by Matt Valentine

INTERVIEW / STEVEN WEINBERG

"The history of science can prevent us from making the mistakes of the past"

*Nobel Prize winner Steven Weinberg talks to **Matt Elton** about his book exploring thousands of years of scientific discovery*

MATT VALENTINE

PROFILE STEVEN WEINBERG
Born in New York City in 1933, Weinberg began his career at the University of California, Berkeley before teaching at institutions including Harvard and the Massachusetts Institute of Technology. His work in the field of theoretical physics has won numerous awards, perhaps most notably the Nobel Prize in Physics in 1979. He is currently a professor at the University of Texas at Austin.

LISTEN TO MORE FROM THIS INTERVIEW historyextra.com/podcasts

IN CONTEXT The development of scientific thought – broadly, the attempt to make sense of the physical universe – is generally understood to have undergone particularly rapid progress in two periods. The ancient Greek world saw contributions from figures including polymath Ptolemy, while the developments of the 16th and 17th-century scientific revolution were generated by thinkers including physicists and mathematicians Isaac Newton and Galileo Galilei, astronomer Nicolaus Copernicus and philosopher and scientist René Descartes.

What inspired you to write this book?

I had been teaching an undergraduate course in the history of physics and astronomy for students who didn't already know a lot about it. As I taught, I became aware that things in the past were quite different from what I had thought. It's not true to say that scientists were reaching for the same goals as us and that they were simply not getting as close as we've come. In fact, they really had no idea of the kind of things that can be learned about the world and the way to learn it. And I began to see the history of science not as the accumulation of facts and theories, but as the learning of a way of interacting with nature that leads to reliable knowledge. It's surprised me how far the great natural scientists of the past were from anything like our modern conception of science.

Heading to the start of this story, how much do we owe the ancient Greeks?

I think the people of the scientific revolution owed them a tremendous amount, particularly the Greeks of the Hellenistic (roughly the third, second and first centuries BC) and Roman periods. For example, Copernicus did not base his theory of the Earth going around the Sun on his own observations or those of his contemporaries in Europe, but on the earlier work of the Greeks, particularly Ptolemy. He saw that Ptolemy's theory could be rectified and made understandable by just changing the point of view from a stationary Earth to a stationary Sun with the Earth orbiting it. The peculiarities of Ptolemy's theory were simply due to the fact that we observe the solar system from a moving platform – the Earth. But Copernicus made no significant observations of his own: he was relying on what Ptolemy had already done. There are many similar examples, too.

However, while we refer to Isaac Newton's work to explain the mechanics of motion and gravity in physics courses today, we don't go back to the Greeks. They are part of our heritage, but their value was mostly in making the scientific revolution of the 16th and 17th centuries possible.

Why were the ancient Greeks able to produce so much important work?

Well, not all of them were. The period that many people think of as the golden age of ancient Greece – the Hellenic period (the fifth and fourth centuries BC), when Athens was at the centre of intellectual life – was not very productive, scientifically. They made some qualitative advances (for example, the philosopher and scientist Aristotle gave a nice argument for why the Earth is a sphere), but the detailed mathematical confrontation of theory and observation we associate with modern physics and astronomy didn't exist. That began in the Hellenistic period, when the centre of Greek thought moved to Alexandria, and the Greek city-states were absorbed into empires, first the Hellenistic kingdoms and then the Roman empire.

I don't know precisely why the change happened at that point. Greek thought in general took a less aristocratic tone, and people who did science also began to be concerned with its practical application. They also became much less religious: the religiosity you find in the work of Plato, which is largely gone with Aristotle, seems to be completely absent by the time you get to the great Hellenistics leading up to Ptolemy.

> The study of the history of science is the **best antidote to the philosophy of science**

How far did the Middle Ages set the ground for the scientific revolution?

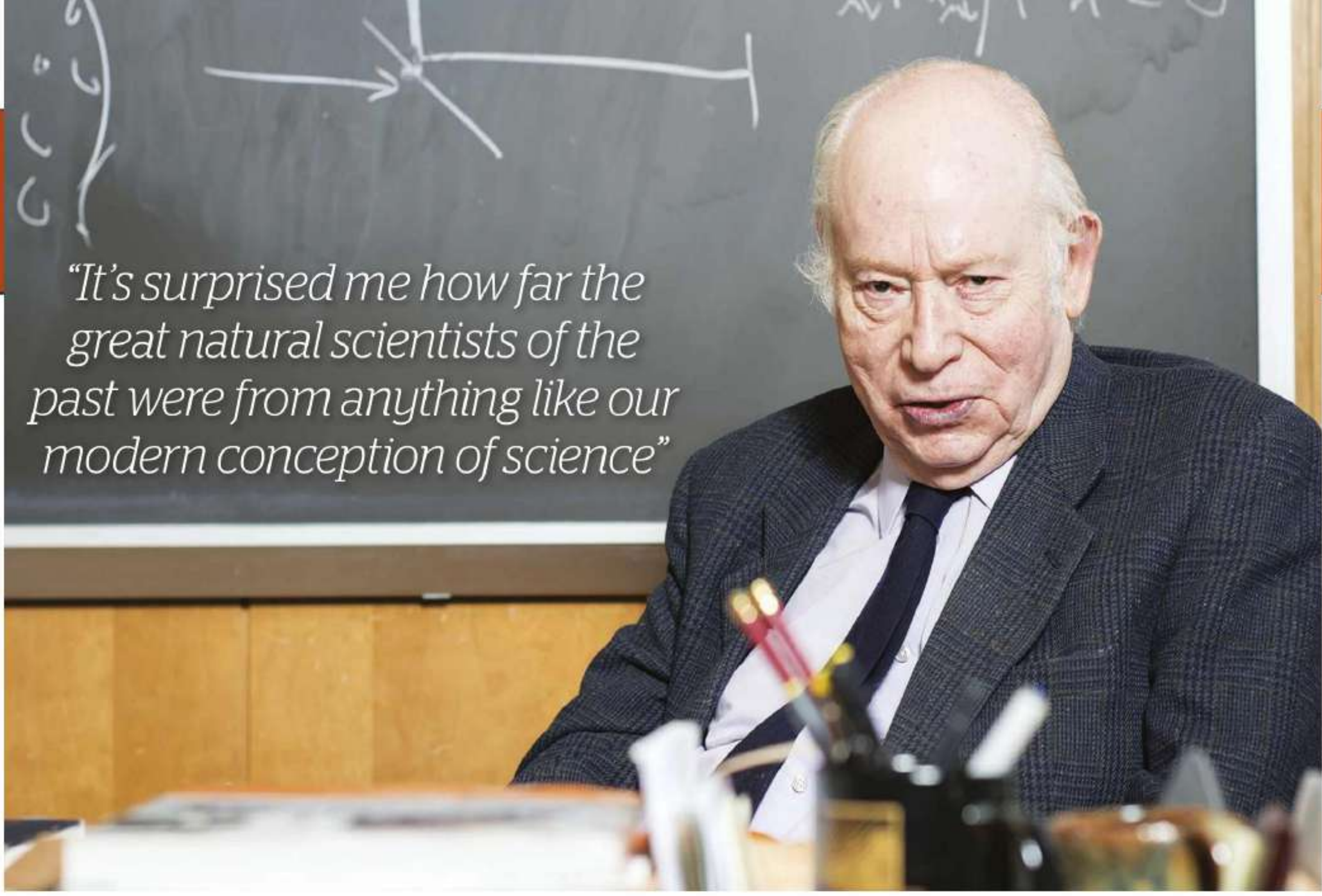
The Middle Ages certainly provided an institutional framework in the form of the great universities. Copernicus was educated at universities in Italy; Galileo taught at Padua and was then a professor at Pisa, although he didn't teach; Newton was always associated with the University of Cambridge. These universities were offshoots of the cathedral schools that had begun a kind of intellectual revolution in the 11th century in Europe. They kept alive the idea of a rational universe governed by law, and in particular when the teachings of Aristotle became firmly fixed in the academic curriculum, the idea of a rational, understandable world became dominant in European thought.

But it wasn't a scientific world. No one in the Middle Ages really had anything approaching our modern conception of science, and they made very little progress towards actual scientific knowledge. There *were* arguments about the possible movement of the Earth, but in the end they didn't lead to anything like the Copernican theory. The Middle Ages was not an intellectual desert, but it wasn't a period that resembles either the Hellenistic age that went before or the scientific revolution that came afterwards.

What was the contribution of Islamic thinkers in this period?

After the decline of the Roman empire in the west, science became, I would say, ineffective and largely absent in the Greek half of the Roman empire. You find no scientific work – at least, I'm not aware of any – during about 1,000 years of the Byzantine empire. During that period, science was kept alive in the world of Islam, first in the form of translations of the great accomplishments of the Greeks and in original work that built on and improved on what the Hellenistic and Roman Greeks had done.

Some of it was very impressive: I think of the work of al-Haytham in optics, who for the first time understood why light is bent when it goes, for example, from air into water. However, although Islamic science in one form or another continued for a few centuries, its golden age was really pretty much over by 1100. If you list the great



"It's surprised me how far the great natural scientists of the past were from anything like our modern conception of science"

names of Islamic science, they're all before that date.

Why that's the case is an endlessly interesting issue. It may have something to do with the appearance of a fiercer version of Islam: for example, Spain was taken over by people from north Africa who formed the Almohad caliphate, which was extremely repressive. There were episodes in which books of scientific or medical technique were burned by Islamic authorities, and the 11th-century philosopher and theologian Al-Ghazali argued explicitly against science because he saw it as a distraction from Islam.

So, had Islamic science run out of steam or was it suppressed by changes in Islam? I don't know the answer, but it's a similar question to that about Greek science. Did that simply run out of steam around 400 or 500 AD, or was it suppressed by the adoption of Christianity? I think that there are good arguments on both sides of both questions.

Are there any characters in this story that particularly stand out for you?

If I understand that in the sense of who I'd like to have a beer with, Christiaan Huygens is a strong contender. He was a 17th-century Dutch polymath who did a huge variety of things: he discovered the rings of Saturn and the formula for centrifugal force, he invented the pendulum clock… I could go on!

MATT VALENTINE

But what stands out for me is that he very explicitly understood the relationship between science and mathematics in a way that had always been muddled. Before him, and perhaps a few other people around at the same sort of time, there had been a large body of thought that felt that science was a branch of mathematics and that its truths could be determined by purely mathematical reasoning. This goes all the way back to Plato, who thought that it wasn't necessary to look at the sky in order to do astronomy – that pure reason was all you needed.

Huygens specifically said we can only make our assumptions because we intend to work on their consequences and see if they agree with observation – and if they don't, we will abandon them. This attitude is one you just don't find very much before.

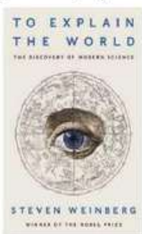
I also think I'd have liked Ptolemy: he expressed his joy of astronomy in a way that was lovely. In just a few lines he wrote that, when he studied the wheeling motions of the planets, he felt his feet leave the ground and stood with the gods drinking nectar.

Are there any misconceptions about science and its history that you'd like this book to change?

One misconception that's been foisted on us by a generation of philosophers of science is the idea of the 20th-century physicist and philosopher Thomas Kuhn that science undergoes discontinuous changes after which it's impossible to understand the science of a former age. I think that's wrong. I think that, even though you can marvel at the importance of every great change in physics, you see the roots of that change in what went before – and you don't forget about it. Indeed, you see the new theory as an improvement on the old theory, not an abandonment of it.

We build on the past, and that, I think, is one of the reasons why the writing of science is different from art history or even political history. We can't say that the Impressionists were right to abandon the photographic realism of the Romantic period, or that the Norman conquest was a 'good' thing. That kind of judgment is silly. On the other hand, we can certainly say that Newton was right and Descartes was wrong about what keeps the planets going around the Sun – there is a definite sense of discovering right and wrong.

That's another important point: science is not just an expression of a cultural milieu, as some historians and sociologists of science have argued. It's the discovery of truths that are out there to be discovered, and it can help prevent us from making the same mistakes as the past. As I was once crass enough to say, the study of the history of science is the best antidote to the philosophy of science. H



To Explain the World: The Discovery of Modern Science by Steven Weinberg (Allen Lane, 2015)

The frontispiece to Thomas Sprat's *History of the Royal Society* (1667) shows its patron, Charles II, being crowned with a laurel wreath

AN EXPERIMENTAL SOCIETY

Over 350 years on from the Royal Society's birth, **Patricia Fara** reveals how its founder members' conviction that experiments should take priority over theories transformed the study of science for good

How long does it take for an organisation to acquire a past? The Royal Society's first history was published in 1667, only five years after it received its Royal Charter. Since there had not been much time for progress, Thomas Sprat's *History of the Royal Society* was more of a manifesto for the future than an account of earlier achievements. Its frontispiece (shown left) optimistically shows King Charles II being crowned with a laurel wreath by the Goddess of Fame, while his name is emphasised by the Society's first president, William Brouncker. However, these diplomatic hints for further financial support went unheeded and the Society's most influential figurehead sits on the right – Francis Bacon (1561–1626), here portrayed in his official robes as King James's lord chancellor.

Trained as a lawyer rather than a natural philosopher, Bacon posthumously set the agenda of the Royal Society by insisting that progress comes not from studying ancient texts, but from experiments. When Isaac Newton claimed that "I feign no Hypotheses", he was reiterating Bacon's prescription that data should take priority over theory, a principle that underpins modern science. At the time, university scholarship was dominated by Aristotelian logic, which reached conclusions by arguing systematically from unchallengeable premises. In contrast, Sprat boasted that the Fellows "never affirm'd any thing, concerning the cause, till the trial was past… for whoever has fix'd on his Cause, before he has experimented; can hardly avoid fitting his Experiment, and his Observations, to his own Cause, which he had before imagin'd."

A 1657 portrait of Francis Bacon, who did so much to shape the agenda of the early Royal Society

GETTY

The Fellows hoped that through measurement and observation, they would **learn how to control nature**

As shown in the coat of arms above Charles's head, the Society's official motto was 'Nullius in Verba' (take nothing on authority), although its policy was closer to Bacon's pithy edict that "knowledge is power". In his extraordinary novel, *The New Atlantis* (published in 1627, after his death), Bacon had envisaged an ideal research community divided into independent project teams that aimed not only to increase knowledge of God's physical world, but also to improve society. Similarly, the Fellows

Experimental pioneer William Harvey, physician to Charles I and James I, uses a stag to demonstrate the circulation of the blood

hoped that through measurement and observation they would learn how to control nature – and that through their commercially viable inventions, they would strengthen the state's rule.

Instruments festoon the elegant arches of this imaginary scientific temple in Sprat's frontispiece. Mostly they are recent adaptations of traditional devices that measure and record the world, but featured prominently to Charles's right is one of the Society's most treasured innovations – the globe of an air (vacuum) pump (shown in greater detail on the next page). Symbolically, as well as practically, the air pump was hugely important. Followers of Aristotle believed that a vacuum is impossible, whereas Baconians declared that this artificially created state would reveal the hidden truths of normality. As the glass sphere was evacuated, ringing bells inside could no longer be heard, flames were extinguished and small animals died, thus demonstrating the necessity of air for transmitting sound, supporting combustion and maintaining life.

An exchange of ideas

Like the Society itself, the air pump originated in Oxford. From the 1640s, small groups of scholars met informally, often in their college studies, to exchange ideas and improve their techniques. Oxford's guru of the new experimental approach was William Harvey, the king's physician who had challenged centuries of anatomy by demonstrating that blood circulates around the body. Inspired by Harvey's work, one researcher tried injecting beer into dogs' veins. This forerunner of transfusion was none other than Christopher Wren. The future architect belonged to an extraordinary community of men, many of them young and unknown, who played a crucial role in the development of British science.

One researcher tried injecting beer into dogs' veins. This forerunner of transfusion was none other than Christopher Wren

Several members of this Oxford group, including Wren, were involved in the foundation of London's Royal Society. Looking back, the two most significant were the chemist Robert Boyle and the inventor Robert Hooke, who worked together on the air pump and later devoted their lives to scientific research. However, the collective enthusiasm at Oxford was more important than any one individual's contribution, and

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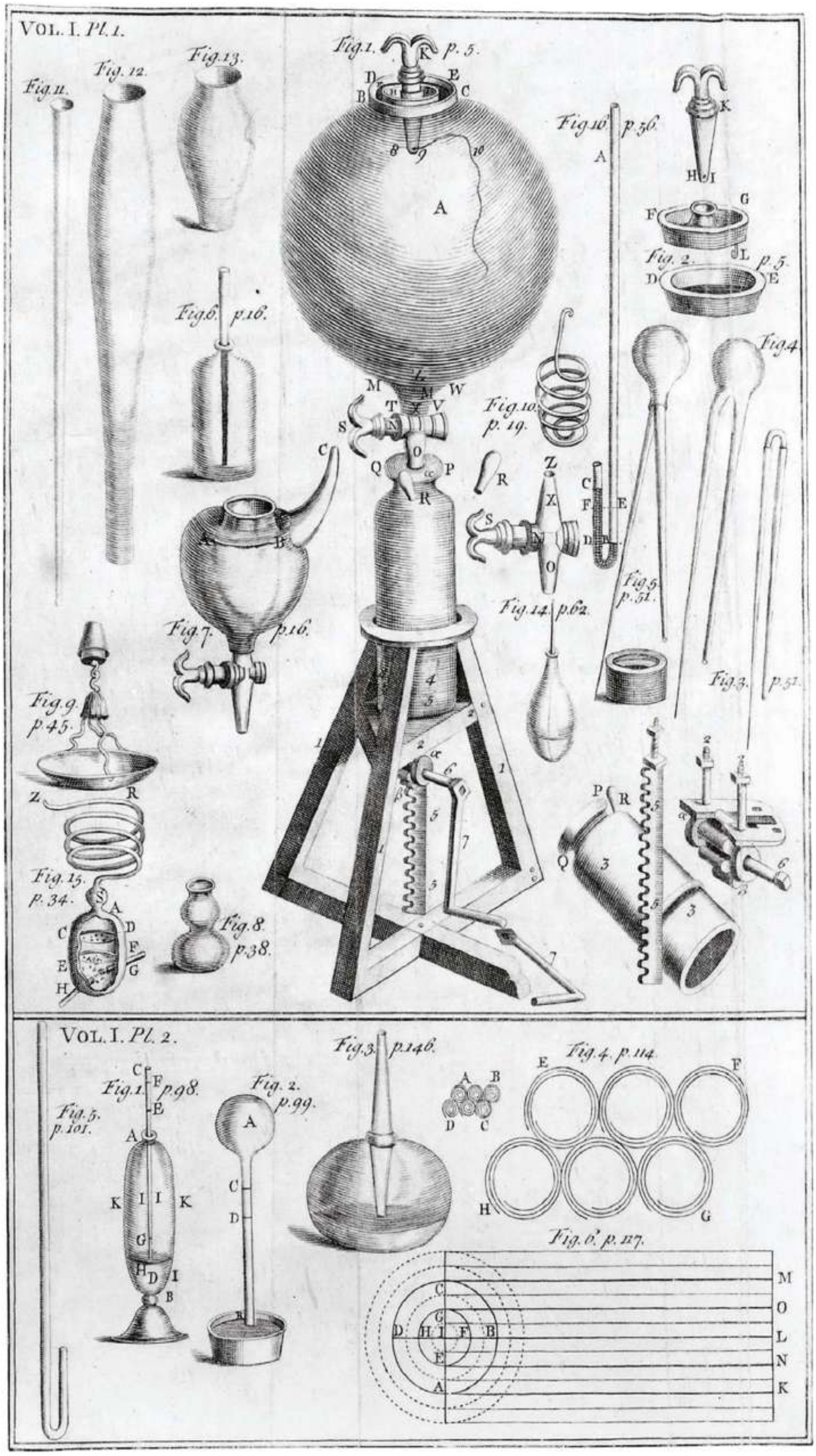


Robert Boyle's diagrams of his apparatus, including his first air pump (1660). Boyle's experiments with the pump helped debunk the Aristotelian theory that a vacuum is impossible

together these experimenters embarked on an ambitious and wide-ranging set of projects: building beehives with glass observation walls, designing accurate micrometer scales for optical instruments, testing new farming methods, explaining the phases of Saturn, developing new drugs, producing artificial rainbows, inventing automata. Not all of their trials were successful, and not all of them were what would nowadays be called scientific, but they were the products of a collaborative research community.

Although Sprat set himself up as the Royal Society's historian, his account of its beginnings glosses over a second important centre of activity – Gresham College, just across the Thames from the naval dockyard at Deptford. Since its opening in 1597, the university-educated mathematicians who taught there had worked closely with local artisans on practical problems such as ship design and terrestrial magnetism, vital for improving navigational compasses. Gradually, the ethos of the school changed as experimental philosophers were appointed to the staff and the latest scientific discoveries were discussed at informal sessions.

Historians have failed to reconcile various versions of exactly what did happen during the late 1650s, but the outcome is clear: Gresham College became the Royal Society's first home. The first meeting took place there on 28 November 1660, soon after Charles II had been restored to the throne, when a group of 12 gentlemen – including several royalists – clubbed together after a lecture given by Wren, the school's professor of astronomy. This was no impromptu gathering, but a pre-planned event at which some important rules and regulations were laid down before impressing on the king what benefits he might reap from a "Society for the Promoting of Physico-Mathematicall Experimental Learning". Over the next couple of years, the founders recruited additional members and further formalised the structure before consolidating their status as 'The Royal Society of London'.

Rather than being a scholarly assembly of dedicated scientists, the Royal Society resembled a club for leisured gentlemen. According to Sprat, it was a democratic institution that welcomed contributions "not onely by the hands of Learned and profess'd Philosophers; but from the Shops of Mechanicks; from the Voyages of Merchants; from the Ploughs of Husbandmen." However, the high subscription charge and metropolitan location effectively restricted the active membership to wealthy Londoners. This supposedly open institution faced another challenge when Margaret Cavendish, a wealthy aristocrat and prolific author, decided to visit the Society in 1667. Boyle reluctantly agreed to perform some experiments for her, but she was the last woman allowed to enter the meeting rooms before the 20th century.

To satisfy the Fellows' demand for entertainment as well as education, Robert Hooke was appointed curator of experiments, the first salaried scientific post in Britain. His research was geared towards devising novel demonstrations that would reinforce the Baconian ethic of gaining knowledge through systematic investigation

BRIDGEMAN

Five founder members of the Royal Society

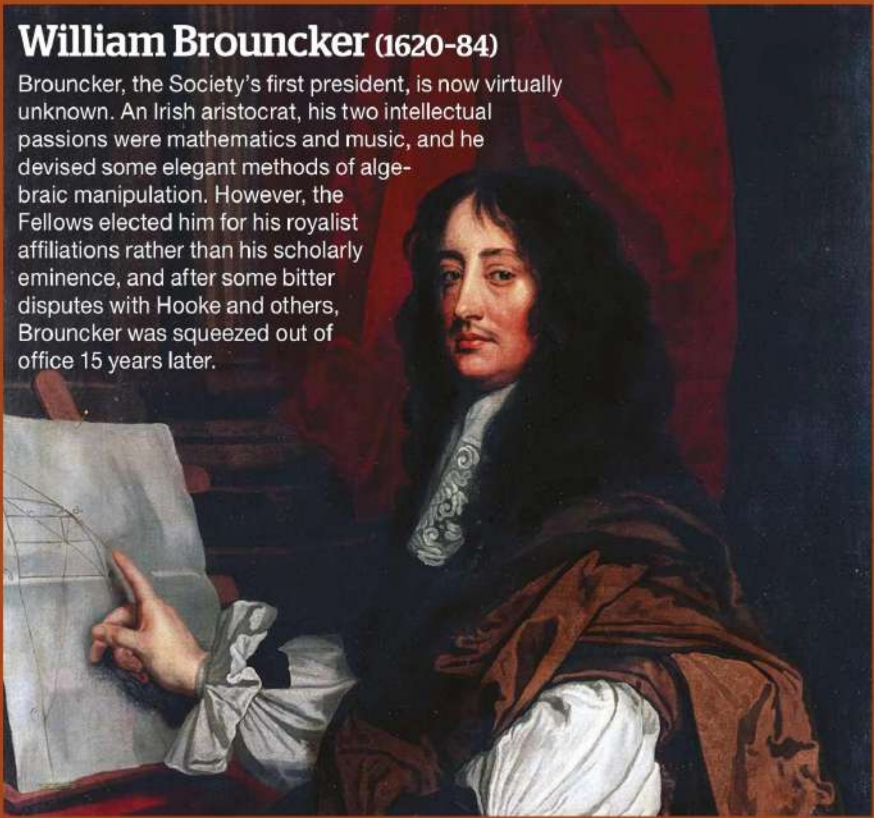
Remarkable thinkers dedicated to "promoting Physico-Mathematicall Experimental Learning"

Robert Boyle (1627-91)

Until recently, only one of the Society's founding Fellows was celebrated as a scientific hero: Robert Boyle. Boyle was a wealthy Irish aristocrat who is famous for inventing the air pump, formulating a law about gases and outlining a corpuscular model of chemistry. Boyle explored the natural world in order to demonstrate the glory of God. A pious yet troubled scholar, his only intimate relationship was with his older sister.

William Brouncker (1620-84)

Brouncker, the Society's first president, is now virtually unknown. An Irish aristocrat, his two intellectual passions were mathematics and music, and he devised some elegant methods of algebraic manipulation. However, the Fellows elected him for his royalist affiliations rather than his scholarly eminence, and after some bitter disputes with Hooke and others, Brouncker was squeezed out of office 15 years later.

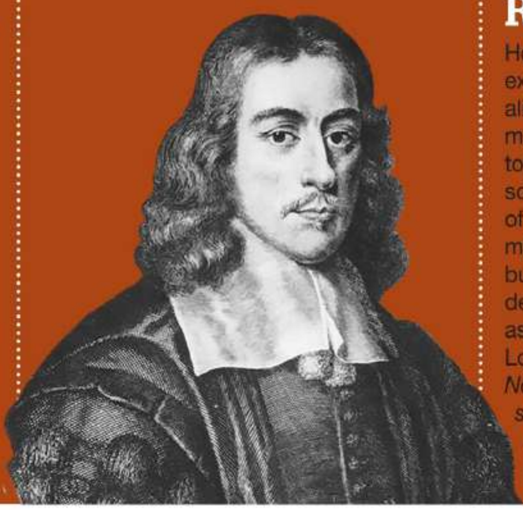


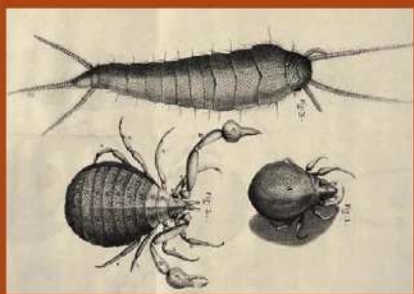
Christopher Wren (1632-1723)

A gifted draughtsman, Wren's modern fame as an architect has overshadowed his closely related passion for scientific experiment and astronomy. He designed the Royal Observatory at Greenwich and was professor of astronomy at Gresham College, London at just 25. One of the youngest and keenest original Fellows, he served as president from 1680 to 1682.

Thomas Willis (1621-75)

Willis studied and practised medicine at Oxford, where he became a professor. A skilled neuro-anatomist and an early convert to William Harvey's circulatory model, Willis established the dominant role of the brain and nervous system in human behaviour. He is now increasingly seen as an important scientific innovator.





Robert Hooke (1635-1703)

Hooke was the Royal Society's first experimental curator. Formerly marginalised, this talented yet cantankerous man is now recognised as a key contributor to both theoretical and practical science. Especially renowned for his law of elasticity and his stunning images of microscopic insects and plants, Hooke built the first vacuum pumps and developed many other fine instruments, as well as playing a key role in rebuilding London after the Great Fire.

No portraits of Hooke exist so we've shown an illustration of a mite, a crab-like insect and a 'bookworm' from his book, Micrographia

GETTY/ BRIDGEMAN ART LIBRARY/GETTY/AKG IMAGES

Knowledge was based not on what people claimed, but on **what they did and what they observed**

and observation. Hooke advertised this experimental approach in *Micrographia*, whose drawings of fleas and lice (see opposite) – those constant invisible companions of lords and labourers alike – so enthralled the diarist Samuel Pepys that he stayed awake all night marvelling at this unfamiliar microscopic world. Hooke was also responsible for looking after the Society's repository, a mixed collection of curiosities that fascinated the public but defied orderly classification.

Membership was restricted, but the Society was effectively international. Reports flowed in from all over the world, while the latest London-based discussions were transmitted outwards by the Society's journal, *Philosophical Transactions*. The first secretary was Henry Oldenburg, a German diplomat accused of trading government secrets, but who made the Royal Society the hub of an extended intellectual community linked together by letters.

Through publishing diagrams, instructions and results, the Baconian Fellows enabled their experiments to be replicated, so that knowledge could (in principle, anyway) be based not on what people claimed, but on what they did and on what they observed. Reflecting the diversity of the members' interests, the early articles covered an impressive range of topics, including ancient coins, oceanic tides, unusual births, geometrical theorems, spectacular loadstones (magnets), mining technology and freak weather events.

Despite their initial enthusiasm, many Fellows were not punctilious about paying their fees. Starved of financial patronage, the Society could afford neither to fund research projects nor to obtain permanent premises, and although symbolically it remained the flagship of European science, its membership declined sharply during the 17th century. The situation was different in France, where the king took a close interest in Paris's Académie Royale, founded in 1666. His pet society had a restricted number of members, but they were appointed by the state and paid to carry out research of national benefit.

ALAMY

The frontispiece of *L'Histoire Naturelle des Animaux* (1671) shows Louis XIV in the palace of Versailles surrounded by instruments of scientific research. The Royal Observatory can be seen through the right-hand window

Louis XIV was an expert in self-promotion and he used his investment in science to advertise his magnificence. In the splendid propaganda picture Louis commissioned (shown above), the large mirror reflects his glory as the Sun King, and the Royal Observatory seen through the window proclaims his generosity. This visit was imaginary, but the differences between the Societies in London and Paris were real. Throughout the 18th century, French research tended to be speculative, mathematical and directed towards state interest, whereas English natural philosophers focused on experiments and commercially viable inventions. Nevertheless, the unfurled map at Louis' feet illustrates how, on both sides of the Channel, Bacon's dictum ruled: "Knowledge is power." H

Patricia Fara is president of the British Society for the History of Science

DISCOVER MORE

BOOKS

- **Science: A Four Thousand Year History** by Patricia Fara (Oxford University Press, 2009)
- **New Atlantis and the Great Instauration** by Francis Bacon (Harlan Davidson, 1989)
- **The Man Who Knew Too Much: the Strange and Inventive Life of Robert Hooke 1635–1703** by Stephen Inwood (Macmillan, 2002)
- **On a Grander Scale: The Outstanding Career of Sir Christopher Wren** by Lisa Jardine (HarperCollins, 2002)

Science Stories
ELECTRICITY

1706 Francis Hauksbee produces electric light

In pursuit of an impressive light show, Hauksbee generated static electricity

A few years ago, a PhD student invited me to travel back with him into the early 18th century. Sitting in a dark unheated room, we huddled around an experimental apparatus that he had made himself using only tools that were available in that era. My task was to turn a handle as fast as I could, but it was not until I slowed down from exhaustion that we saw what the original experimenter had promised: purple and green lights flickering eerily inside a glass sphere. Thrilled, we imagined how amazing this effect must have been in a pre-electrical age, when artificial lighting meant candles and oil lamps.

The first person to demonstrate this gaseous glow was Francis Hauksbee (c1666–1713), a former draper who had somehow gained favour with Isaac Newton to be put in charge of the experimental programme at London's Royal Society. Far from being active scientists, most Fellows were wealthy gentlemen who demanded spectacular displays to justify their subscription – and it was Hauksbee's responsibility to provide weekly entertainment.

His own research focused on air pumps, machines that sucked out gas to create a near vacuum, and for one meeting he revealed how a small piece of luminescent phosphorus would continue to glow even in an apparently empty space. When he heard that shaking a barometer could cause a mysterious glimmer to appear in the tube above the mercury, Hauksbee decided to investigate further.

Hauksbee soon devised a stunning display for impressing the Fellows. By adapting the rotating wheel of a knife-grinder, he made an empty globe spin round – but not too fast, as I once discovered for myself. The student's inherited instructions had also neglected to point out that the wheel-turner is an assistant scarcely worth mentioning, often a servant or a wife. Instead, the experimenter who gains the glory is the man (inevitably at the time) who places his hands against the glass so that the gas inside lights up. Although he did not realise it immediately, Hauksbee had invented the first machine to generate static electricity.

A second refugee from the cloth trade, a Canterbury dyer called Stephen Gray,

> Francis Hauksbee was put in charge of the **experimental programme at the Royal Society**

introduced still more dramatic electrical displays. In his efforts to explore how charge could be transmitted from one place to another, Gray became increasingly ambitious, outgrowing his room to drape long wires around the country estates of accommodating Fellows. Keen to find out what sort of objects might be affected at a distance, he tried out soap bubbles, a red-hot poker, a sirloin of beef, a map, an umbrella and eventually, a small boy from a charity school.

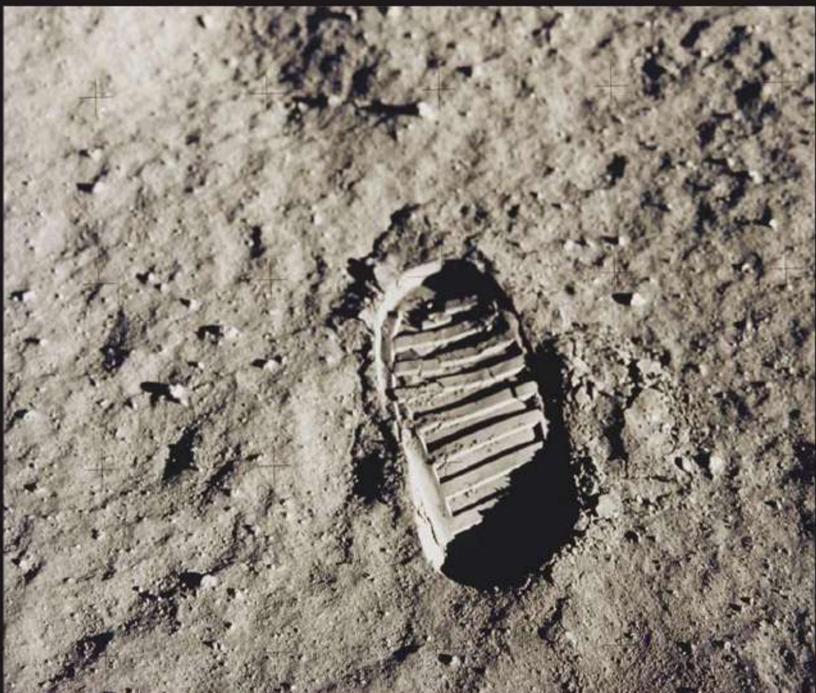
Like Hauksbee, Gray converted his exploratory experiments into theatrical performances. Using two strong clothes lines, he suspended a child from the ceiling to hang horizontally in a room that was darkened to heighten the mystique. After the victim had been charged up with an electrified glass tube, sparks flew and crackled whenever he was touched, and small feathers or brass filings leapt up through the air towards his outstretched hand.

Within a few years, performers all over Europe were entertaining lecture audiences and dinner party guests with this apparently magical trick. Wielding his tube like a conjurer's wand, an electrical experimenter could claim to control the powers of nature. It was, enthused one commentator, "an entertainment for angels, rather than for men". H

Words: Patricia Fara

ALAMY

12 GIANT LEAPS FOR MANKIND



ASTRONAUT BOOTPRINT ON THE LUNAR SURFACE, 20 JULY 1969; APOLLOARCHIVE.COM–NASA

In a feature first published in *BBC History Magazine* in 2009, 12 historians nominate the moments that they consider to be among humanity's greatest leaps forward

1 Meat sets us apart

Carnivorism

Probably Africa, c2.5 million years ago

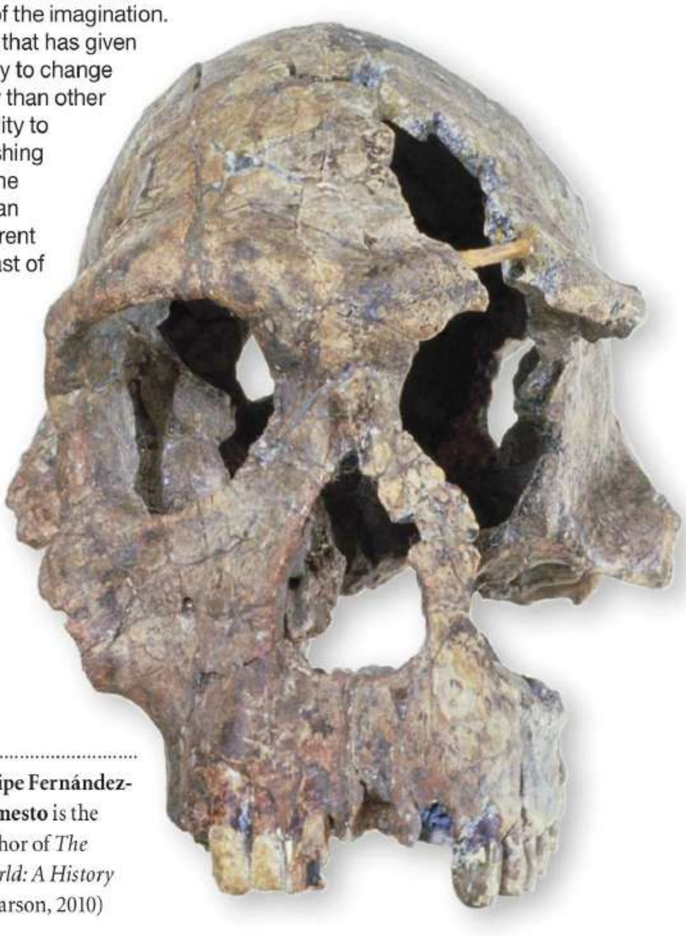
Chosen by Professor Felipe Fernández-Armesto, University of Notre Dame

I don't believe in human progress but if you held a pistol to my head and said I had to come up with something of evolutionary advantage to humans, I would say that among other primates the relatively early carnivorism of our hominid ancestors was of enormous importance. If you are carnivorous it gives you access to fats and proteins that are not available in such concentrated form in non-meat food sources. Not only that but although the first hominid carnivores were almost certainly scavengers, in the very long run meat-eating launched them on the trajectory that led to hunting.

Hunting stimulates the faculties of anticipation because you need to have the ability to see what isn't there, to see what's behind the next tree or over the next hill. I believe that an accidental by-product of this faculty of anticipation is humanity's super endowment of the imagination. It is our imagination that has given humans the capacity to change with greater rapidity than other species and the ability to form a really astonishing range of cultures. The features of the human past which are different from those of the past of other animals are traceable to our imagination, which is traceable to anticipation and in an indirect way you can trace it all back to carnivorism.

Nowadays there is a very broad consensus that carnivorism began about 2.5 million years ago. We don't know why it happened but I'd postulate that it was an evolutionary consequence of our lack of other advantages compared with rival species.

Actually we are pretty poorly designed animals because we're slow, lack agility, have only one stomach, weak fangs and don't have tails. We're behind in almost everything and that's why we need more plentiful abundance of anticipation than other creatures similar to ourselves.



A hominid skull from around two million years ago, when our ancestors were probably carnivores

Felipe Fernández-Armesto is the author of *The World: A History* (Pearson, 2010)

Getting involved: Greeks in conversation during the fifth century BC

2 The people take control

The advent of politics

Greece, seventh century BC

Chosen by Professor Paul Cartledge, University of Cambridge

I understand 'politics' in the very strict sense, that's to say taking it from the Greek word polis meaning 'city', 'city-state' or (best of all) 'citizen-state'. The ancient Greeks invented the idea of the citizen and also the idea of citizens coming together on the basis of some sort of political equality to take decisions about matters of communal concern. We don't know much about who the early politicians were, but we do know that, for example, in the little city of Dreros on Crete there was a public assembly passing communally binding decisions in 600 BC, so politics must have been flourishing already.

Without the invention of this citizen state and the politics and procedure it entailed, democracy would be unthinkable. We do our politics very differently today, more in a Roman way, but nevertheless the very idea of the 'political' – people coming together and taking decisions, not by divine right but because they are citizens – goes back to the ancient Greeks.

Paul Cartledge is the author of *Ancient Greek Political Thought in Practice* (CUP, 2009)

JOHN READER–SCIENCE PHOTO LIBRARY/ALAMY

3 Every man has a voice

Democracy

Greece, 507 BC

Chosen by Dr Peter Jones, formerly of Newcastle University

Democracy was invented in 507 BC by an Athenian called Cleisthenes. Over the course of the next 100 years in Athens and elsewhere in the Greek world it developed into a full-blown radical system where all male citizens over 18 took all decisions about the running of their own state. The consequence was that there was no such thing as politicians. Even a great Athenian political figure like Pericles had no authority over the people's assembly. All he could do was try to persuade them that his view of things was right, but if they didn't like it then they could reject it.

Athenian democracy has been heavily debated, but I think that it was remarkably successful. It ran for 180 years until it was destroyed by the Macedonians in 323 BC, and while the charge has been made that it was like mob rule, the Athenians strike me as having been admirably governed.
I believe the people were perfectly capable of taking sensible decisions. To give one example, they could, being the people who made all the decisions, have voted themselves bags of gold and pensions for life – but they never did.

Modern 'democracy' can be traced back to Athens, yet what we in the UK live in today is actually an elective oligarchy, where we choose 650 MPs to make decisions on our behalf. There is nothing wrong with elective oligarchy per se, but I wish that it were not called democracy because it seems to me that the Athenian experiment was so remarkable, powerful and appealing compared to the feeble version we have today. Evidence: the handling of the MPs' expenses scandal.

Peter Jones is the author of *Vote for Caesar: How the Ancient Greeks and Romans Solved the Problems of Today* (Orion, 2009)

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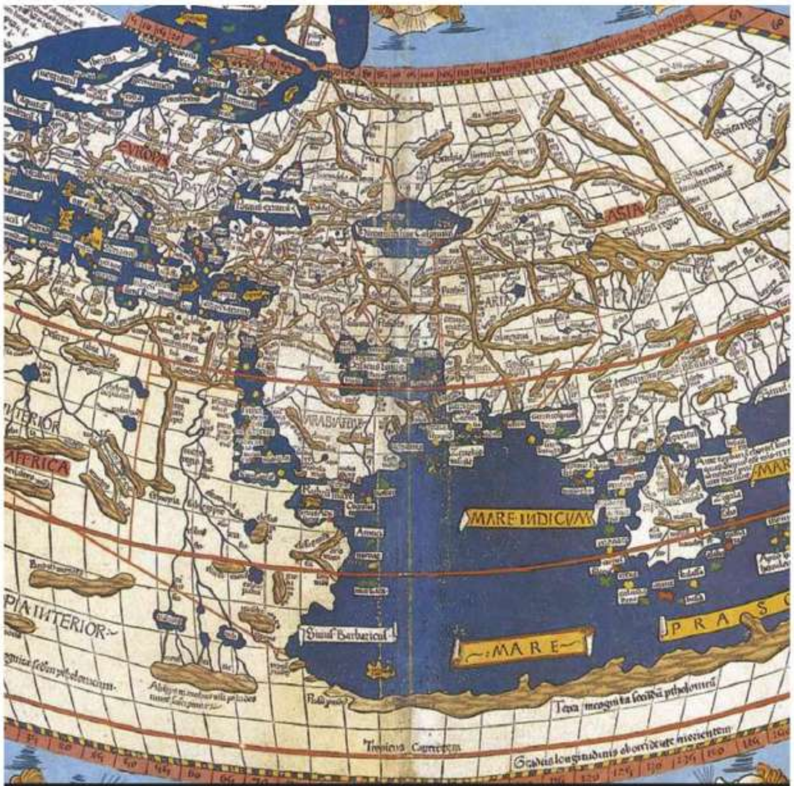


A 15th-century map of the world illustrating a Latin edition of Ptolemy's *Geography*

4 Seeing the world as it is

Ptolemy's *Geography*

Roman empire, c150 AD

Chosen by Professor Jerry Brotton, Queen Mary University of London

In around AD 150, Ptolemy was working in the library of Alexandria, then one of the greatest repositories of Greek learning. He wrote his *Geography*, which defined the discipline of geography and laid down the principles of global mapping. There were no maps in the book but what the *Geography* offered was a geographical description of the world and an explanation of how maps could be drawn. It allowed scholars to map the world for the first time in history.

Interestingly, the text wasn't really taken up initially. This was in the late Hellenistic, early Christian moment and Christianity had no interest in the rather abstract geometrical mathematical notion of how you plot the world on a map. It was the Arabs who kept Ptolemy going, in places like Baghdad until it reappeared in Italy in the 14th century. Renaissance geographers produced new editions of the *Geography* and employed Ptolemy's principles to try to map the expanding world. It was also used by the likes of Christopher Columbus and some of the Portuguese explorers who were sailing east, such as Vasco da Gama.

Ptolemy is known as the father of geography and for 1,500 years everything pivoted around him. Even the modern map is based on the kind of projections that Ptolemy offered. In a way, Ptolemy was a kind of classical Google. Google gives you the tools to map as you want – whether to see your own home, or Washington DC, or Korea. Well, in a sense, that is what Ptolemy did. He didn't proscribe what geography is, but said here are the tools to understand your place in the world, and that for me is why he is so enduring.

Jerry Brotton is the author of *A History of the World in Twelve Maps* (Penguin, 2013)

Early learners: Italian students reading in the 14th or 15th century

5 Teaching the masses to read

Alexander of Villedieu's *Doctrinale*

France, 1199

Chosen by Professor Robert D Black, University of Leeds

Throughout the Middle Ages and well into the early modern period, literacy was inextricably associated with Latin. However, until the end of the 12th century, the methods of teaching Latin were extremely long and drawn out, based on a system whereby pupils read and memorised Latin texts for years. It was a scheme that was largely suitable to the clerical elite.

Then along came Alexander of Villedieu, a French grammarian and teacher who was private tutor to the nephews of a bishop in northern France. He devised a fast-track method to teach Latin using simple rules and written in verse so that his pupils could memorise it more easily. When the bishop asked his nephews how they were doing in their learning of Latin, they quoted back a few verses given to them by their teacher. The bishop thought it was such a good idea that he encouraged Alexander to write a whole grammar.

That book was *Doctrinale*, which became one of the great medieval bestsellers. Its influence and use spread throughout Europe and, on the basis of such simplified methods for teaching Latin, a great movement of mass literacy began. This new type of education was much more rapid and better suited to the aspirations, intentions and professional needs of the laity. *Doctrinale* therefore marked the first major step in the move towards a wide-ranging and extended secular lay education.

Robert D Black is the author of *Humanism and Education in Medieval and Renaissance Italy* (CUP, 2008)

6 The triumph of the law

Magna Carta

England, 1215

Chosen by Professor David Carpenter, King's College, London

Magna Carta was a turning point in British and world history because it was the first time a ruler was subject formally to the law. It became a great barrier against arbitrary rule and arbitrary kingship and it is that fundamental principle that resonates down the ages. Magna Carta seemed very important in the 17th-century struggle of the parliament against Charles; it seemed equally important to the founders of the American constitution, and of course it still reverberates today.

The background to the charter was a society that was becoming more cohesive, with a greater sense of community. There were political ideas about rulers who should be subject to law and govern for the benefit of their society not just themselves. These came up against a very intrusive form of kingship, which extracted huge amounts of money from England on the one hand but gave little in the way of peace and justice on the other.

King John was the final straw. He spent many years and large sums trying to regain Normandy after it was lost in 1204 – and once he failed to do so in 1214, with his treasure spent, he was a sitting duck. He was also a murderer and a lecherous womaniser who evoked fear and loathing on a very personal level. There was a huge degree of animosity against him, which doesn't explain the broader grievances but helps to explain why it all came to a head with the rebellion in 1215.

You can see how important Magna Carta was by the fact that when John tried to renege on the deal there was a great civil war. The only way the minority government of John's son felt they could win this war and secure the peace after he died in 1216 was by reissuing the charter. Throughout the 13th century the charter was constantly cited and referred to. It became then what it has always remained: a touchstone of just and lawful rule.

David Carpenter is the author of *The Struggle for Mastery: Britain 1066–1284* (Penguin, 2004)

PHOTO SCALA, FLORENCE

7 Overturning the old astronomers

Galileo explores the heavens with his telescope

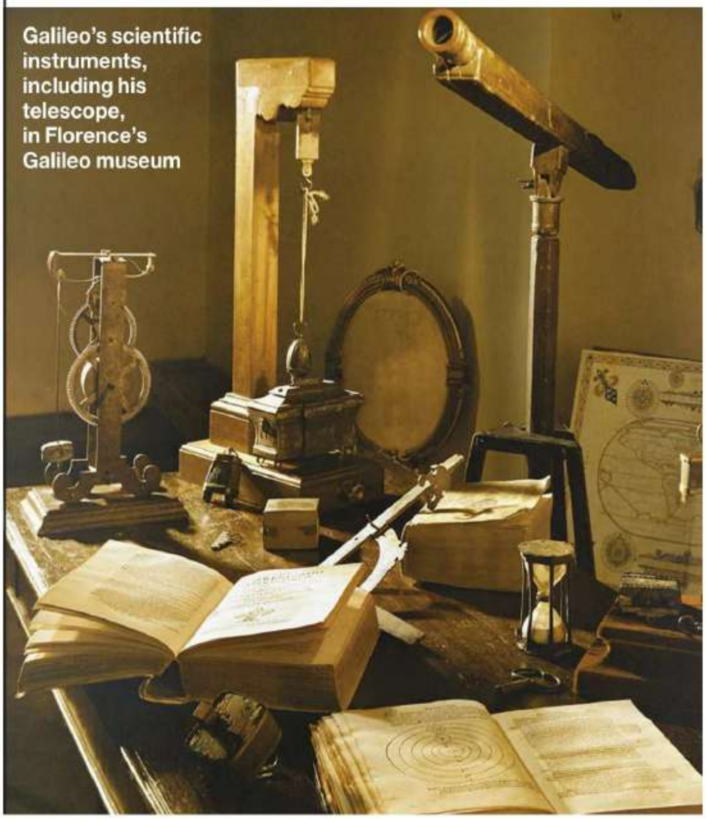
Italy, 1609

Chosen by Professor Colin Russell, The Open University

When Galileo became the first person to turn a telescope to the skies, it changed our view of the universe. He discovered new facts about the Sun, Moon and planets, which were totally incompatible with the old theory that the sky above Earth was unchanging and perfect. Instead they strongly supported the rival and newer heliocentric theory of Copernicus.

Galileo's telescope stimulated him to write his contentious book *Dialogue Concerning the Two Chief World Systems* (1632), which more than anything else helped to establish Copernicanism. It also led to his trial and impeachment before the Roman Catholic church. The old system Galileo discredited had been almost unthinkingly adopted by the church and built into their picture of the universe. It fitted nicely with biblical data, so for hundreds of years it remained the accepted view. However, scripture (unless interpreted woodenly) can also be compatible with Copernicanism. Galileo recognised this in a letter he wrote in 1615. But a scientific proof of Copernicanism had to wait until 1838! At the trial, Galileo was found guilty and it wasn't until the 20th century that the Vatican finally came to agree with him.

Colin Russell was co-author of *The Rise of Scientific Europe 1500–1800* (Hodder, 1991). He died in 2013



Galileo's scientific instruments, including his telescope, in Florence's Galileo museum

AKG IMAGES

8 Explaining how the body works

William Harvey reveals the circulation of the blood

England, 1628

Chosen by Dr Allan Chapman, University of Oxford

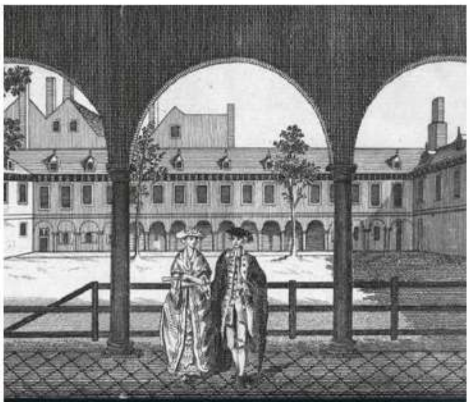
The circulation of the blood might sound like something we all accept but, in fact, it wasn't discovered until 1628. Before that it was believed that blood came from food in your liver, then entered the heart, where it was heated before it shot out into the veins, not the arteries. This is why Shakespeare and people like that talk about the blood "coursing through their veins" instead of their arteries.

William Harvey was the physician to James I. Through a meticulous study of what you might call the plumbing of the chest he came to the conclusion that the heart didn't heat the blood, it pumped it into the arteries. He knew from Fabricius that the veins had stepladder valves in them, which Harvey realised helped the blood get back to the heart, completing the circuit. Harvey was working before the microscope and didn't know how the blood got from the arteries to the veins, but he made a very bold guess that this was done by tiny vessels so small he couldn't see them. He was perfectly right, of course, and we call them capillaries.

It was a discovery of colossal importance. There have been numerous advances since, but I'd suggest that circulation was so crucial because without it the others wouldn't have emerged. You couldn't undertake modern surgery or give an injection without circulation and can you imagine any modern medical discovery without the knowledge of the blood pumping from the heart?

Harvey's theory was published in 1628 in a book called *On the Motion of the Heart and Blood* and you might think that he would have been inundated with patients afterwards. Yet it almost ruined his career as a doctor. In those days, doctors were very conservative and wouldn't make innovations – this was associated with quacks. Good doctors, it was thought, dispensed medicine and diagnosed purely in accordance with the way the ancients had taught. So, curiously enough, the greatest medical discovery of all time caused a considerable amount of financial distress to its discoverer!

Allan Chapman is the author of *England's Leonardo: Robert Hooke and the Seventeenth-Century Scientific Revolution* (Taylor & Francis, 2004)



Gresham College, the original meeting place of the experimental society in 1660

9 Launching the scientific age

The founding of the Royal Society

England, 1660

Chosen by Dr Patricia Fara, University of Cambridge

When King Charles II was restored to power, a group of men who had been working in Oxford came back to London and decided to set up a society for carrying out experimental research. It was the first national scientific society to be created anywhere in Europe. Although it was rather like a gentlemen's club, it did allow people to come together specifically to carry out experiments, do research, disseminate new theories and collect data. Within a few years there was a similar society in Paris and soon they started proliferating all over Europe.

Organisations dedicated to scientific research are very important and I think historians should write more about how science is enabled, not just the great achievements. Too much history of science has been about heroes such as Newton and Darwin, and not enough about institutions. For me, the big overriding question is how science has become so integral to today's society: I believe the Royal Society was the institutional foundation that made modern science possible.

Patricia Fara is the author of *Science: A Four Thousand Year History* (OUP, 2009)

10 A micro-revolution in our understanding

The discovery of the very small

Europe, 17th century

Chosen by Professor Jim Bennett, former director of the Museum of the History of Science

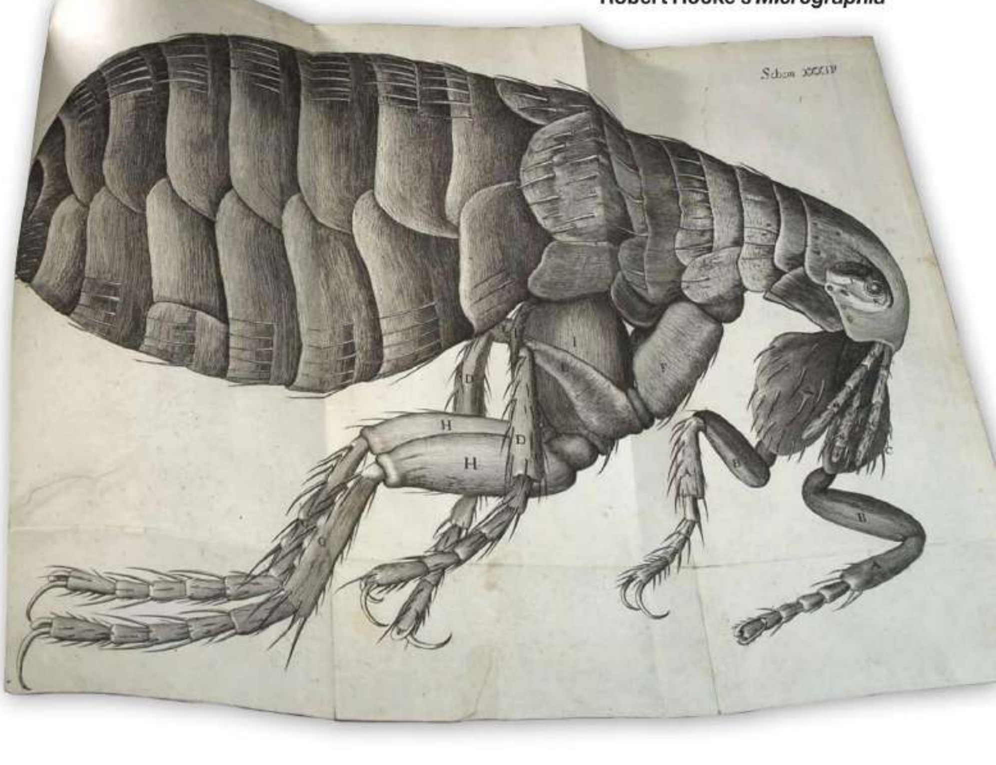
It is such a fundamental, taken-for-granted notion of modern science that we explain the properties of things by going beneath the superficial appearance to the micro-world. But like anything we take for granted, it was made in history.

The microscope was known from the earliest decades of the 17th century. At first it was just a toy that you could go and buy at a fair. It didn't tell you anything about the natural world because although you could look at little things, nobody who was interested in explaining the world was yet saying that everything depended on them. Still, the microscope was the technology that made people believe there was a route to the very small. It was no longer just a matter of speculation. You could engage with it empirically.

A new mode of explanation that assumed an underlying micro-reality began later in the century and one of its principal exponents was Robert Hooke, author of *Micrographia* (1665). He articulated very clearly that the micro-world is a bit like a clock with lots of springs and wheels. Just like we can open up a clock, Hooke said we could open up the actual world to see how it works, and the tool for doing so was going to be increasingly powerful microscopes. A lot more had to happen before we got to where we are now in our beliefs about explaining the macro with the micro, but I think it all started in the 17th century.

Jim Bennett is co-author of *London's Leonardo: The Life and Work of Robert Hooke* (OUP, 2003)

A very small flea looks rather large in Robert Hooke's *Micrographia*



Stephenson's famous 'Rocket' locomotive in an early photograph

11 Powering the modern world

The development of the steam engine

Britain, 18th century

Chosen by Professor Jeremy Black, University of Exeter

Unlike the atom bomb, for example, there was no single invention with the steam engine. First you had the stationary steam engine where the most important person was Thomas Newcomen. Then James Watt improved its efficiency and its capacity to generate power. Later on, the stationary steam engine was transformed into the locomotive with George Stephenson.

What the steam engine enabled people to do was transform themselves beyond the existing constraints of energy use, meaning that human society could develop in all sorts of ways. Now we know that the environmental consequences of industrialisation were detrimental, but on the other hand life would have been totally different if we had remained shackled by the manufacturing, energy and communication systems before the steam engine.

The long-term implications of steam power were everything we understand by modernity. It gave us the ability to speed up existence and overcome the constraints under which all other animal species operated. We were not radically different in organisational terms from other animals, which have language, the capacity for acting as a group and systems of hierarchy. For much of human history that was how we were, but we moved to a very different tune when we had everything that is understood by modernity. It was the steam engine that set that in motion.

Jeremy Black is the author of *The Power of Knowledge: How Information and Technology Made the Modern World* (Yale, 2015)

Indians in Calcutta celebrate their independence in 1947

12 Ending the empires

The Montagu-Chelmsford Report

British empire, 1918

Chosen by Professor Peter Robb, School of Oriental and African Studies

After the First World War there was a feeling in Britain that something should be done to recompense India for its war effort. At the same time, there was growing political organisation and agitation in India and the business of government had grown so much that the colonial authorities needed to involve more Indians in it.

These were the origins of a report written by Lord Chelmsford, viceroy of India and Edwin Montagu, secretary of state for India. The report said the British should take definite steps towards giving Indians self-government. This was the first formal admission, at least by the British, that non-European people could rule themselves under a modern system of government. All subsequent discussions were not about *whether* India should have self-government but *when* India should have self-government.

Most British thought it would be some time in the next 100 years. They didn't imagine it could happen in 1947, but once on that particular bandwagon it was hard to get off. Indians did not think enough was being offered, or that the offer was sincere; and so they were organising, especially under Gandhi, setting an example for future political movements.

Nothing like this had been done anywhere else in 1918 and no one had really conceded that it could be done. The whole trend of European countries then was to get more colonies. You certainly didn't give them up. You might give them some rights, but no one in authority was saying you should set them up as separate self-governing nations.

But that is what the Montagu-Chelmsford report said they were going to do in India. It was a profound psychological shift. In a sense, all British decolonisation flowed from that moment and from its idea that a new nation-state could be made by non-Europeans, who some people had thought were incapable of self-rule. (Indians had, however, shown themselves to be adept at law and politics.)

India was the biggest country under European domination by far, so when it appeared that it was getting self-government everybody else started talking about decolonisation. The report gave strength to the view that empire was illegitimate and that it was possible to transfer power into new nations. The example was eventually taken up by other countries and India itself was a major force on the United Nations decolonisation committee. **H**

Peter Robb is the author of *A History of India* (Palgrave Macmillan, 2011)

Interviews were conducted by Rob Attar

HEAVEN &

- **Ptolemy's maps**
  The world-shaping second-century geographer
- **Science stories: Herschel's new planet**
  The 1781 discovery of Uranus
- **A brief history of astronomy**
  The 5,000-year quest to understand our universe
- **A rail revolution**
  How rail travel transformed Britain and the world
- **Galileo and the telescope**
  His extraordinary celestial discoveries
- **The industrial revolution**
  How industry's great innovators were celebrated

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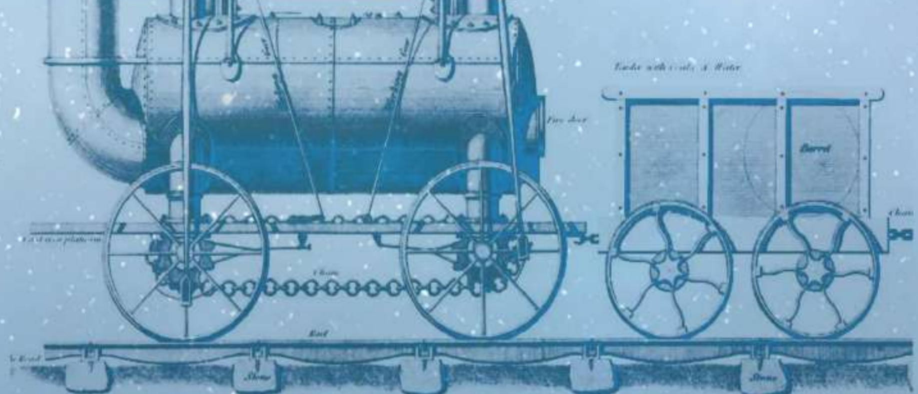
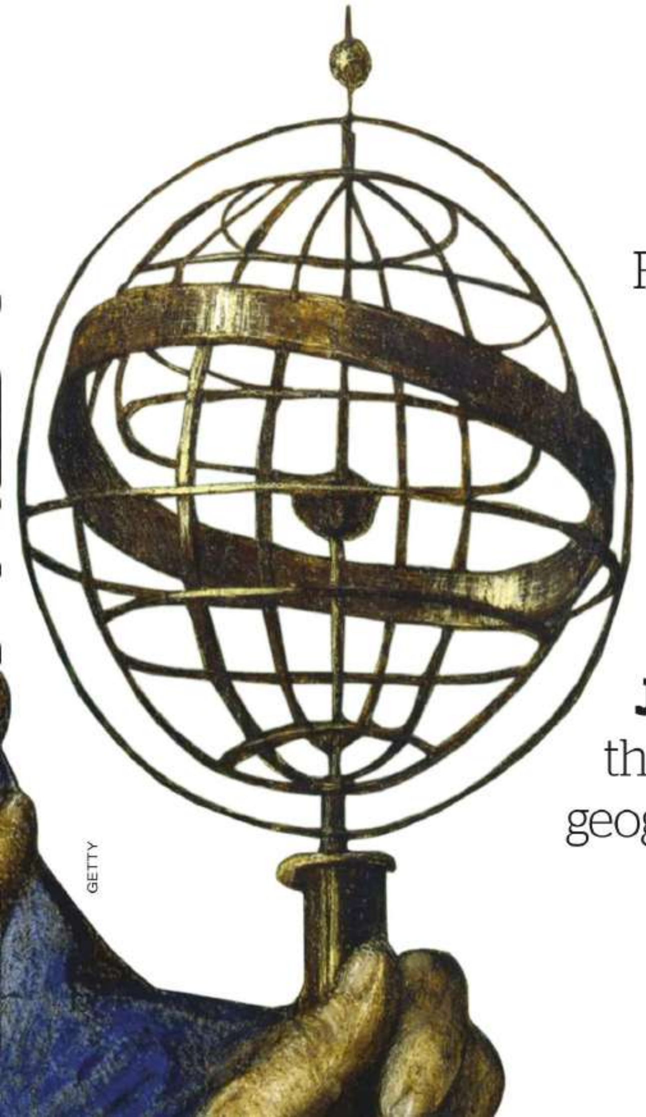
EARTH



Joos van Gent's c1475 portrait of Ptolemy, who "offered subsequent generations a mapping tool kit"

THE FATHER OF MODERN GEOGRAPHY



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From Columbus's expeditions to the Google Earth app, our understanding of the Earth owes a huge debt to one extraordinary scholar. **Jerry Brotton** introduces the second-century geographer Ptolemy

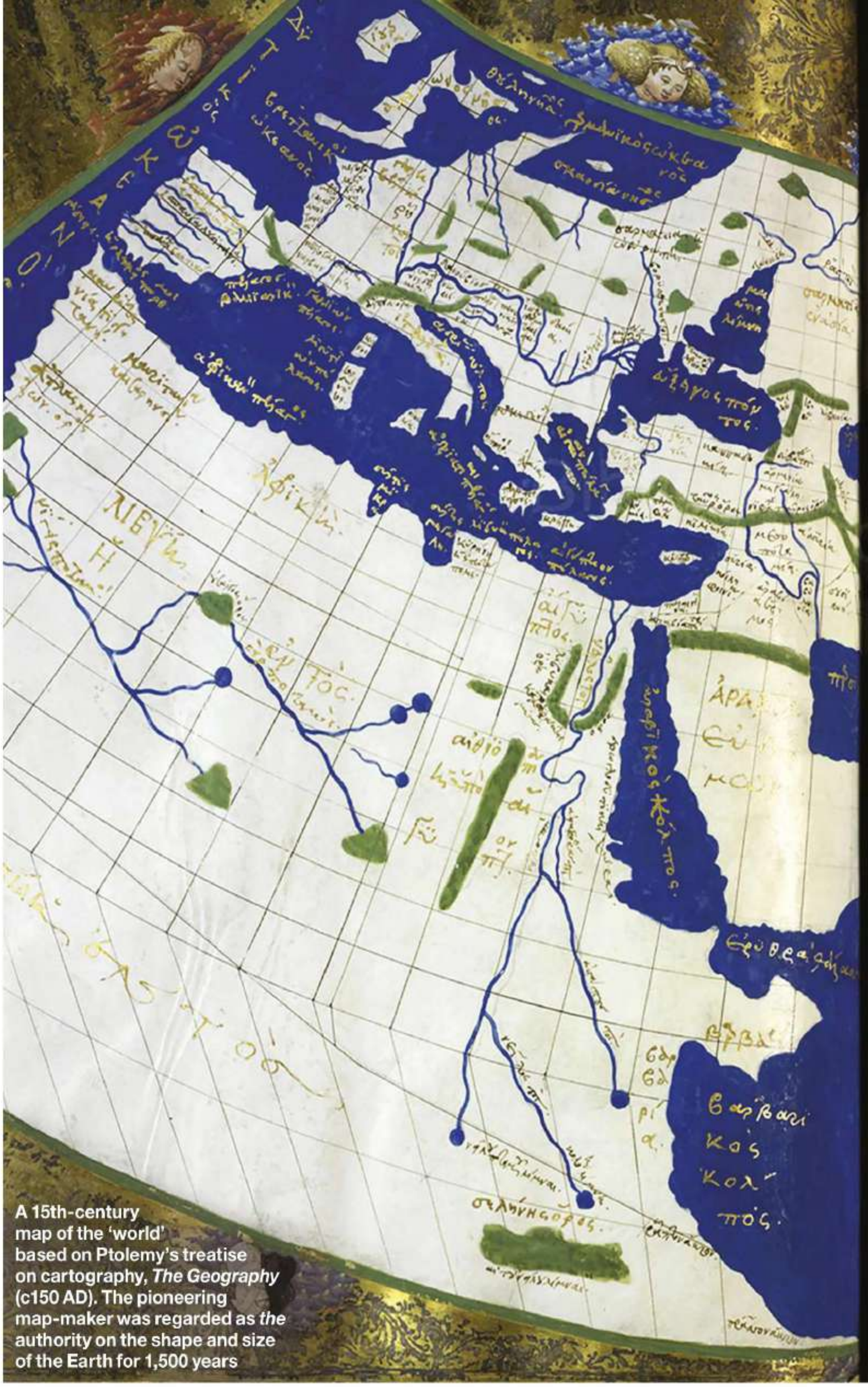
Ask any geographer to name one individual responsible for founding their discipline and they are likely to answer: "Ptolemy." Claudius Ptolemaeus (c100–c170 AD) lived in second-century Alexandria, where he wrote the *Geographike Hyphegesis* (c150 AD), known today simply as the *Geography*. It defined geography, explained how to draw a world map and offered a gazetteer of over 8,000 locations in the known world.

For the next 1,500 years, virtually every map-maker accepted Ptolemy's *Geography* as the authority on the shape and size of the world. Columbus and Magellan both used Ptolemy to embark on their voyages of discovery, and even 16th-century map-makers like Gerard Mercator and Abraham Ortelius, who knew that Ptolemy's geographical knowledge was limited, drew maps in homage to the man they regarded as 'the father of modern geography'.

The basic principles of Ptolemy's map projections remain in use to this day – even Google's 'Earth' application uses a projection first invented by him – and yet his life, as well as his methods, remain a mystery. What little we know is based on later Byzantine sources. He was a native of Ptolemaic Egypt, which, during his lifetime, was already under the control of the Roman empire. Taking the name 'Ptolemaeus' suggests he had Greek ancestors and 'Claudius' indicates he possessed Roman citizenship.

Circuits of the Earth

What is known is that Ptolemy worked at the Alexandria Library, founded in c300 BC, the repository of all written knowledge, which held thousands of manuscripts from across the Greco-Roman world. Some of the greatest classical scholars worked there, including the mathematicians Euclid (c325–265 BC) and Archimedes (c287–212 BC), the poet Callimachus (c310–240 BC) and the astronomer – and one of the earliest librarians at Alexandria – Eratosthenes (c275–194 BC). By Ptolemy's time, the library, like the Hellenic culture it represented, was in decline, ravaged by warfare, neglect and looting. For Ptolemy this decline represented a unique opportunity to summarise nearly a millennia of Greek geography. By drawing on what remained of the library's resources, Ptolemy compiled his *Geography*, to "show the known world as a single and continuous entity" and to "investigate the Earth's shape, size, and position with respect to its surroundings".



A 15th-century map of the 'world' based on Ptolemy's treatise on cartography, *The Geography* (c150 AD). The pioneering map-maker was regarded as *the* authority on the shape and size of the Earth for 1,500 years

The Greeks had been drawing maps – onto a physical medium, such as wood, stone or bronze, called *pinax* – for centuries, and writing about them in works usually entitled *Periodos Ges* (literally a 'circuit of the Earth'). Homer describes a circular, flat Earth encircled by water in his *Odyssey*, but by the fifth century BC Pythagoras and Parmenides concluded that if the universe was spherical, then so was the Earth.

Ptolemy **drew a geometrical net of latitude and longitude** over the world

In *Phaedo* (c380 BC), Plato described the Earth as "round and in the centre of the heavens", "marvellous for its beauty" and circular perfection. Aristotle agreed, adding climatic zones, which led his disciples to introduce rudimentary lines of latitude and longitude. Using astronomy and geometry, they pieced together a map of the known world which they called the *ecumene* – an inhabited 'dwelling space'. Although none of these maps survive, a reconstruction of

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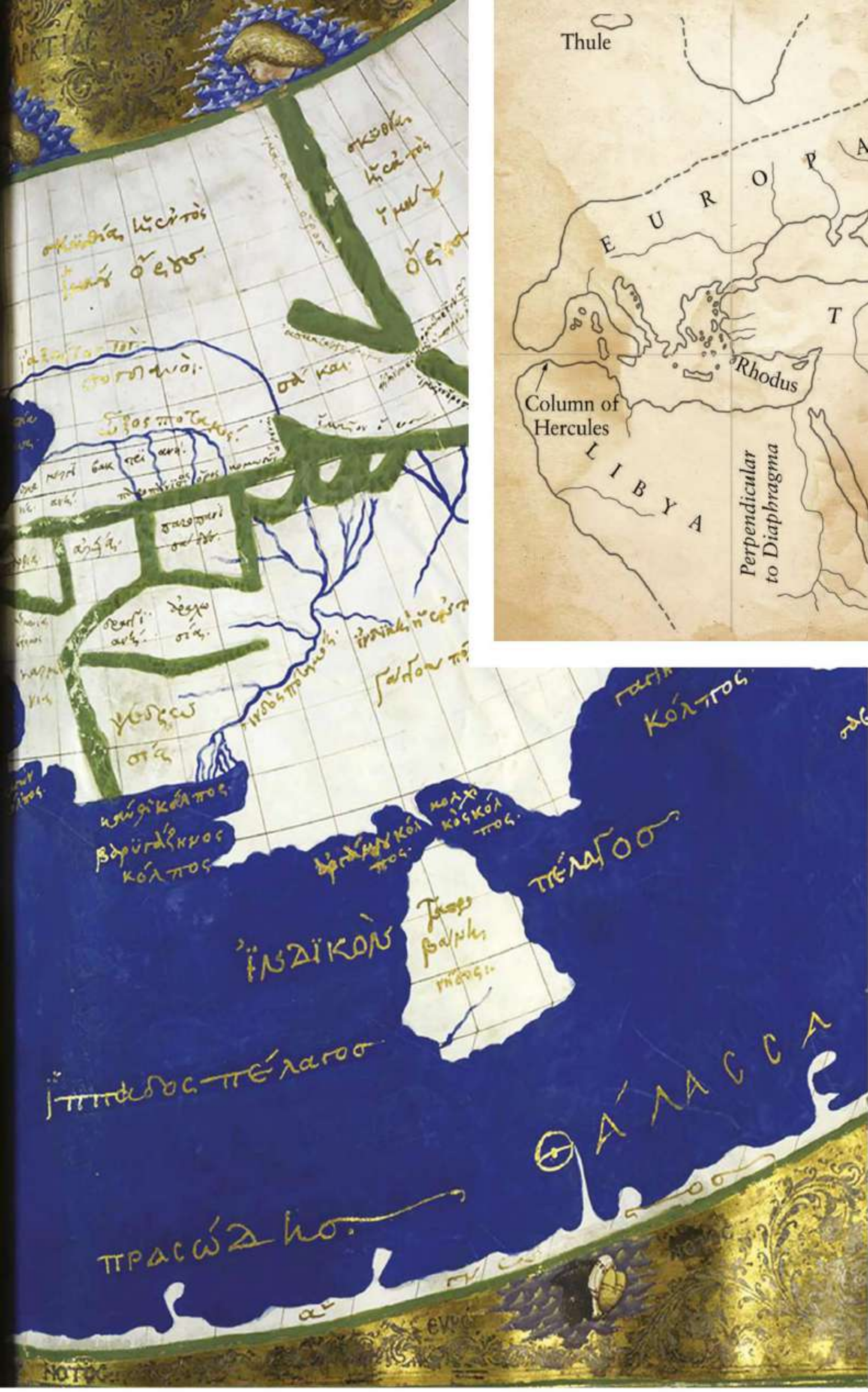
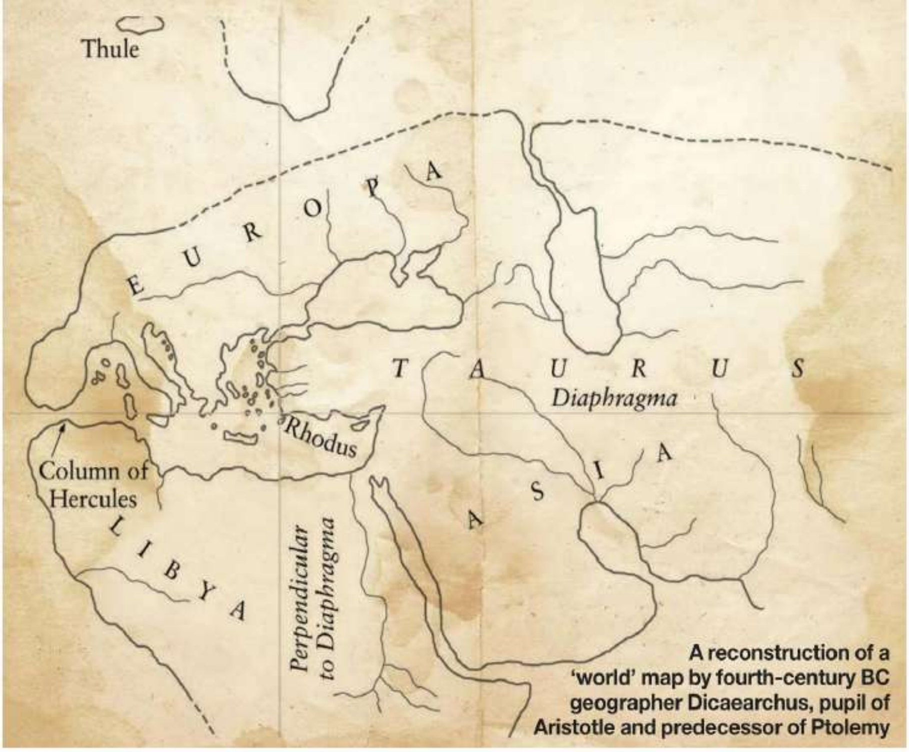




A reconstruction of a 'world' map by fourth-century BC geographer Dicaearchus, pupil of Aristotle and predecessor of Ptolemy

the world map (see top right) of Aristotle's pupil Dicaearchus of Messina, who worked between c326 and 296 BC, shows how the Greeks began to understand the size and shape of a world centred on Rhodes.

Ptolemy was also able to draw on some remarkably accurate calculations of the size of the Earth, including those of Eratosthenes. Using a sundial, Eratosthenes measured the angle cast at midday on the summer solstice at both Aswan and Alexandria, which he believed were on the same meridian, 5,000 stades apart (a Greek stadion was between 148 and 185 metres). He calculated the angle between the two places as one-fiftieth of a circle. This led him to conclude that the globe had a circumference of 250,000 stades (37,000–46,000km). Considering the Earth's circumference at the equator is 40,075km, his calculations were extraordinarily accurate.

From Vietnam to the Canaries

When Ptolemy came to write his *Geography*, he synthesised this mass of Greek learning and drew a geometrical net of latitude and longitude over the world, preferring the consistency of mathematics over the unreliable gossip of travellers' tales (what the Greeks called *akoe*, or 'hearsay'). He began by defining geography as "an imitation through drawing of the entire known part of the world". He then divided the globe's circumference into 360° (based on the Babylonian sexagesimal system), with the known world stretching from west to east through an arc of 177°, from the Canary Islands to Cattigara in modern-day Vietnam. The known world's breadth was estimated at just over half its length, from Thule (Iceland), 63° north of the equator, to the region of 'Agisymba' (modern-day Chad), 16° south of the equator, a latitudinal range of just over 79°.

Yet expanding the world in this way made it difficult to project the globe onto a flat surface. Ptolemy knew that no map projection could ever represent the globe without distortions, so he used Euclidean geometry to offer two different methods of making a world map. On the first cone-like projection the meridians were drawn as straight lines converging at an imaginary point beyond the north pole, with the parallels shown as curved arcs of different lengths, centred on the same point. Ptolemy explained that anyone could draw such a map by using a swinging ruler and referring to his tables of latitude and longitude in the later books of the *Geography*.

He conceded that this projection had its drawbacks: on a globe, parallel lines diminish south of the equator, but on Ptolemy's projection they actually increase in length. His compromise was to propose meridians forming acute angles at the equator. This was fine for the Greeks, who regarded the habitable world as ending somewhere in the Sahara, but it would prove a problem for 15th-century pilots when they tried to sail down the African coast.

He therefore offered a second projection that was "similarly proportioned" to the globe by drawing curved parallels and meridians. The trigonometry was more complex, and Ptolemy confessed that it was

This engraved allegory of astronomy, taken from *Margarita Philosophica* (1508), shows a crowned Ptolemy being guided by the muse Astronomy

harder to construct a map on this projection, as the curved meridians could not be drawn with the aid of a swinging ruler.

However, Ptolemy cheerfully advised readers to "hold on to descriptions of both methods, for the sake of those who will be attracted to the handier one of them because it is easy". He was, in effect, offering subsequent generations a mapping tool kit and a gazetteer of places to which they could expand almost indefinitely, building up an ever-changing map of the world as new data became available.

Mapping the future

But there was also another astonishing reason for the success of Ptolemy's projections. The earliest surviving manuscripts of the *Geography* with maps come from late 12th-century Byzantium. There is no concrete evidence that Ptolemy ever drew his own maps. Instead, he transmitted geographical data in digital form, using a series of numbers and diagrams that allowed later map-makers to adapt it. Perhaps we should therefore regard Ptolemy as the first digital geographer.

When Columbus and Magellan planned their epic voyages to the east by sailing west, they both turned to Ptolemy to support their expeditions, and for good reason. Ignoring Eratosthenes's calculations, Ptolemy had estimated the length of a degree as 500 stades, underestimating the global circumference by as much as 10,000km, or more than 18 per cent of the Earth's actual circumference.

He preferred the consistency of mathematics over **the unreliable gossip of travellers' tales**

Looking at a world map based on Ptolemy's calculations, it is no wonder that Columbus and Magellan believed it was possible to sail west to get to the east. Without Ptolemy's mistaken calculations, they would probably have never set off on such daunting voyages, and the shape of the age of discovery might have looked very different. H

Jerry Brotton is professor of Renaissance studies at Queen Mary University of London. He is the author of *This Orient Isle: Elizabethan England and the Islamic World* (Penguin, 2016)

DISCOVER MORE

BOOKS

- **The History of Cartography, vol. 1** eds JB Harley and David Woodward (Chicago, 1987)
- **A History of the World in Twelve Maps** by Jerry Brotton (Penguin, 2013)

Science Stories

ASTRONOMY

1781 William Herschel sees a new planet

A 19th-century illustration shows William Herschel and his sister Caroline at their 40-foot telescope

Despite CP Snow's contention in 1959 that there is a gulf between scientists and 'literary intellectuals', two centuries ago poets were fully aware of the latest scientific discoveries. After a drink-fuelled night discussing Homer, the medical student John Keats wrote his famous lines comparing his own wonderment with that of "some watcher of the skies/When a new planet swims into his ken". Keats was referring to William Herschel (1738–1822), the astronomer who had enlarged the solar system with a seventh planet, now known as Uranus.

Historians like pinning discoveries down to an exact time and place, but in this case it's simply not possible. Uranus had already been spotted many times, but was always assumed to be a star. In 1781, after noticing that '34 Tauri' moved across the skies, Herschel suggested it was a comet. He clung to that belief for two years, long after other experts had decided it was a planet. In 1783 he was rewarded for his discovery by the king with an annual salary and an invitation to Windsor.

Diplomatically (or ingratiatingly?) Herschel named his planet George's Star, but European astronomers objected to such chauvinism, and it was only in 1850 that British authorities finally adopted the German proposal of Uranus.

An immigrant from Hanover, when Herschel observed Uranus he was earning his living as a musician in Bath. Displaying the passion of a late convert, he started dedicating his entire life to astronomy. He also forced his younger sister, Caroline (1750–1848), to abandon her musical career and act as his assistant. Their success depended on hard work and unusually large telescopes that collected enough light to make small, distant objects visible.

Craftsmen often recruited daughters or wives to help run family businesses, but the Herschels developed an exceptionally close relationship. By day, Caroline polished mirrors, calculated data and compiled catalogues, while at night she brought coffee to keep them awake as they worked together in the dark and cold.

Awards for William poured in, but recognition for Caroline came only after his death. Whereas he is credited with discovering Uranus, she is celebrated for being the first woman to report a new comet, which she had found by patiently trawling the skies with a small telescope very different from the gigantic instrument they used together. Acting as a tourist guide, she had conducted eminent visitors through its tube. "Come," she heard George III say to the Archbishop of Canterbury, "I will show you the way to Heaven!"

Herschel suggested that Uranus was a comet and **clung to that belief for two years**

Looking back, it seems that William treated her appallingly, but like many women of the period, Caroline colluded in this downtrodden state. "I am nothing, I have done nothing," she wrote; "a well-trained puppy-dog would have done as much" – a self-abnegating remark that cannot simply be dismissed.

In 1835, the Royal Astronomical Society made Caroline an honorary member, formulating this early statement of equal opportunities: "While the tests of astronomical merit should in no case be applied to the works of a woman less severely than to those of a man, the sex of the former should no longer be an obstacle to her receiving any acknowledgement which might be held due to the latter."

The language may be outdated, but the sentiments are modern. H

Words: Patricia Fara

ALAMY

A BRIEF HISTORY

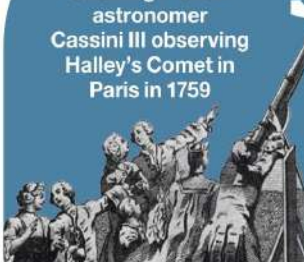
Heather Couper explains how our understanding

Druids celebrate the summer solstice at Stonehenge, 1983

1 *Time and place*

Midsummer sunrise at Stonehenge is so iconic that the place swarms with New Agers and latter-day Druids watching the Sun climb above the Heel Stone. However, the **latest research suggests the Druids' ancient predecessors watched the Sun set from the Heel Stone on midwinter's day**. Either way, Stonehenge marks the extremes of the calendar.

Even more impressive is the 300 BC monument at Chankillo, Peru, where **a line of 13 towers marks points at which the Sun rises** throughout the year. Yet preliterate civilisations didn't just keep time by the heavens: **the Polynesians used the stars to navigate** from Hawaii to New Zealand **– a distance of over 7,000km –** out of sight of land!



An engraving showing French astronomer Cassini III observing Halley's Comet in Paris in 1759

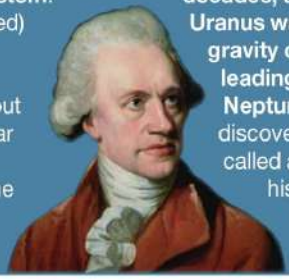
5 *A matter of some gravity*

While Cambridge University was closed due to the plague in 1665, Isaac Newton returned home to Woolsthorpe Manor, Lincolnshire, where **he formulated the law of gravity – which stipulates how every body in the universe attracts every other**. But he didn't publish it until persuaded to by Edmond Halley, who used Newton's law to calculate that comets seen in 1531, 1607 and 1682 were the same visitor. And **it was this law that led Halley to predict the return in 1758 of the comet that bears his name.**

Andreas Cellarius's c17th-century illustration of the Copernican system, placing the Sun at the centre of the universe

6 *New worlds*

On 13 March 1781, **a German amateur astronomer living in Bath doubled the size of the solar system.** William Herschel (pictured) discovered a "curious either nebulous star or comet" – which turned out to be a planet twice as far from the Sun as Saturn. Herschel wanted to name it Georgium Sidus, after King George III, but the name Uranus was internationally accepted. **Over the decades, astronomers found that Uranus was being pulled by the gravity of a more distant planet, leading to the discovery of Neptune in 1846.** Pluto, discovered in 1930, was at first called a planet but, uniquely in history, its status as a planet was revoked in 2006.



10 *The quest for life*

There's only one place in the universe where we know life certainly exists, and that is, of course, Earth. However, **the next shattering discovery in astronomy is likely to be life on another world.**

Mars is probably home to micro-organisms, according to the Labelled Release experiment on the Viking landers that Nasa sent to the Red Planet in 1976. Other possible habitats in the solar system where life could exist include the ice-covered oceans on Jupiter's moon, Europa, and Saturn's satellites Enceladus and cloud-wreathed Titan.

There's plenty of scope for life out there – after all, **as of today, there are more than 4,000 planets circling other stars.** And in 2007, scientists of the SETI programme (the Search for Extraterrestrial Intelligence) began operating a vast new receiver in California, the Allen Telescope Array, that may detect radio broadcasts from **aliens that have evolved from bacteria to intelligence.** H

Heather Couper is a broadcaster and the author, with Nigel Henbest, of *Philips Stargazing 2018* (Philips, 2017)

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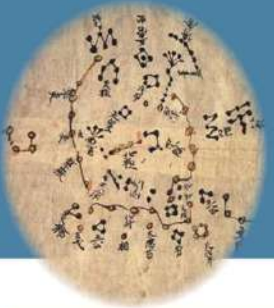
OF ASTRONOMY

of space has developed over the past 5,000 years



A Chinese star chart of the sky seen from the northern hemisphere, c700 AD

2 *Mirror of the Earth*

Chinese astronomers were the first to make accurate records of the sky. They regarded the heavens as a mirror of the Earth, with the stars representing different regions of China. So an exploding star in a star pattern would indicate a rebellion in a corresponding province.

We have Chinese astronomers to thank for the earliest known records of Halley's Comet – in 240 BC – and an account of a supernova, from AD 1054, whose remains today form a tangled mass of gas called the Crab Nebula.

3 *Ordering the heavens*

The Greek philosopher **Pythagoras was among the first to question the widely held view that the world was flat** when, in the sixth century BC, he taught that the Earth must be a sphere, because of the shape of its shadow on the Moon during a lunar eclipse. Over 200 years later Aristarchus suggested the Earth moves round the Sun – yet his idea didn't take off. Instead, it was left to Ptolemy (pictured below) to leave the Ancient Greeks' most lasting imprint on astronomy when (around AD 150) **he concluded that the planets moved in small circles carried by larger circles, centred on the Earth.** His theory was unchallenged for 1,400 years.

4 *The Earth moves*

Our perception of mankind's importance in the universe changed forever in 1543, when Polish canon Nicolaus **Copernicus published a book arguing that the Earth did not sit at its centre**. Instead, it was merely a planet orbiting the Sun. Copernicus had come to this conclusion over 30 years earlier, but he largely kept it to himself. His case was proven in 1610, when Galileo Galilei – in Padua, Italy – turned his telescope to the skies.

Galileo saw that Jupiter was accompanied by four moons (overturning the argument that the Earth couldn't be in motion as it would leave the Moon behind) and observed the changing phases of Venus, which showed this planet must be orbiting the Sun. The **church banned Galileo's books** but, from then on, no one seriously doubted that the Earth had been dethroned from the centre of the universe.

7 *Powerhouse of the stars*

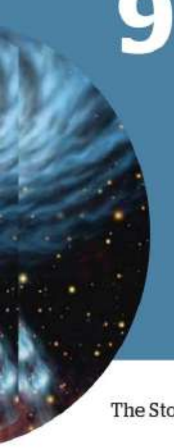
"On the subject of stars… we shall never be able by any means to study their chemical composition." So wrote the French positivist philosopher Auguste Comte in 1835. But only two decades later, German chemists Gustav Kirchhoff and Robert Bunsen proved him wrong. **They identified elements in the Sun by comparing the dark lines in its spectrum** of colours with laboratory spectra of elements, such as hydrogen and iron.

In the 1920s, British astronomer Cecilia Payne (pictured left) worked out the relative proportions of the elements, and **proved that most of the universe is made of hydrogen.** It led to an understanding that the powerhouse of the stars was basically **a hydrogen bomb running in slow motion.** And astrophysicist Fred Hoyle squared the circle by showing how elements are built up in stars. So the gold in your wedding ring is nothing less than the product of an exploding star.

Digital artwork of what the Big Bang may have looked like

8 *The Big Bang*

In the 1920s, American astronomer Edwin Hubble, along with former mule-driver Milton Humason, **found that galaxies are racing apart from each other.** The universe is expanding, suggested Belgian priest Georges Lemaitre, because it was born in an exploding "primeval atom" – what we now call the Big Bang. This was proved in 1965, when American scientists Arno Penzias and Robert Wilson discovered **a faint background of radio waves – the afterglow of the Big Bang.**

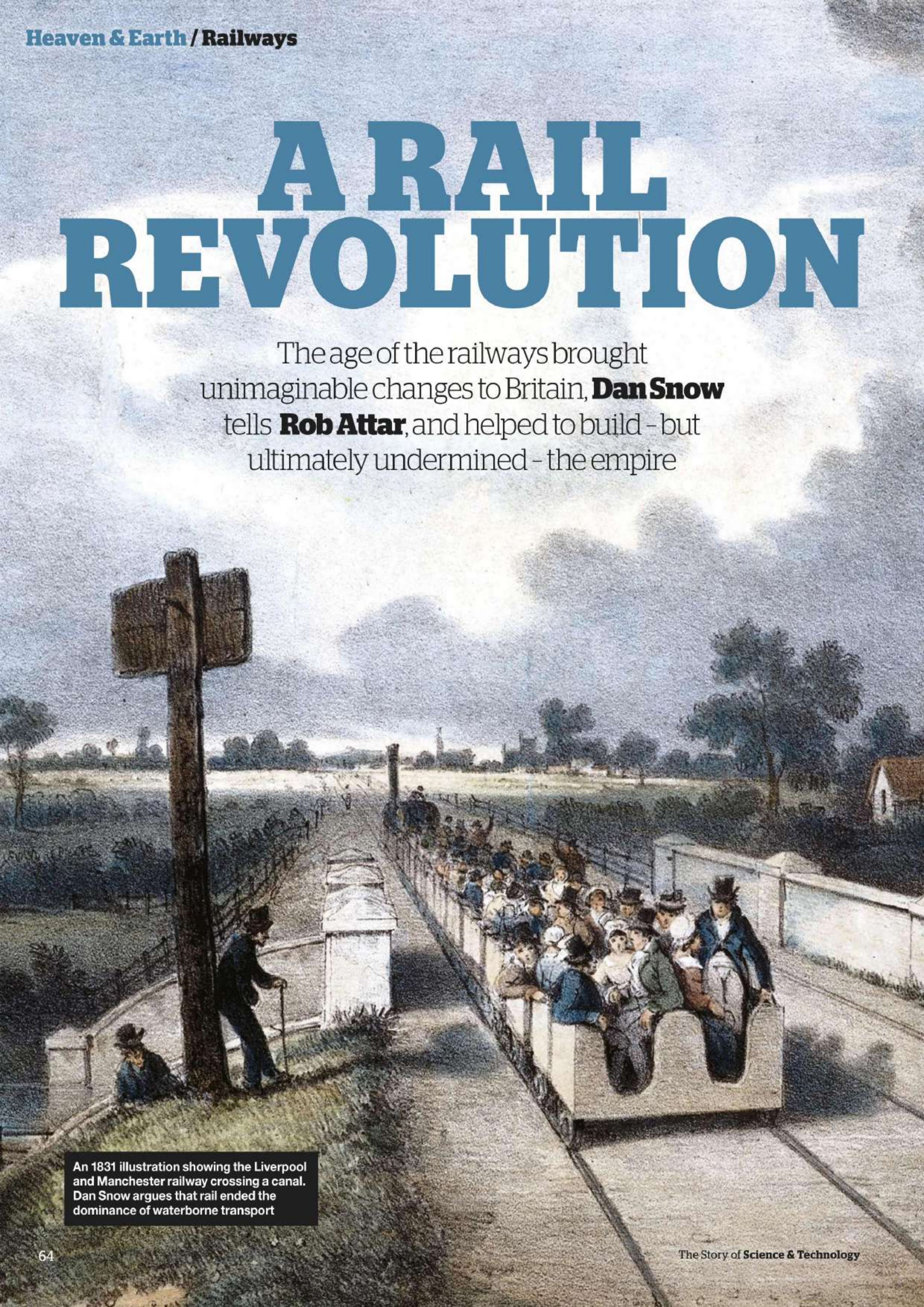


9 *Black and brilliant*

British army scientist Stanley Hey was perplexed in February 1942. He was investigating what seemed to be an outburst of German radar jamming – but it moved around the sky during the day. **Hey realised that the emission came from the Sun, and instigated the science of radio astronomy.** Since then, radio astronomers have discovered pulsars – dense balls of matter only the size of a city, but with the mass of the Sun. And they have found giant black holes. **These cosmic monsters weigh as much as a billion suns,** and their gravity is so powerful that light can't escape. As the gas from the stars swirls round the black hole, it shines as brilliantly as hundreds of galaxies in an incandescent flickering maelstrom that astronomers call a quasar (illustrated on the left).

A RAIL REVOLUTION

The age of the railways brought unimaginable changes to Britain, **Dan Snow** tells **Rob Attar**, and helped to build – but ultimately undermined – the empire



An 1831 illustration showing the Liverpool and Manchester railway crossing a canal. Dan Snow argues that rail ended the dominance of waterborne transport

Why did the railway revolution come to Britain first?

Coal was a massive reason for this. Because of the nascent industrial revolution in the 18th century and because there were no big indigenous forests left in the country, Britain, and London in particular, needed energy from coal.

London had a voracious appetite, so the coal trade was absolutely booming in a way that it wasn't elsewhere in the world. That coal was arriving from Newcastle by ship, down the east coast. In order to take the coal to Newcastle there was a huge network of trackways right across north-east England. Trackways – used initially by horses and carts – created much less friction than travelling over the rough ground.

It was only a matter of time before people started experimenting with steam engines on these trackways. Britain had already done a lot of the early running in the development of steam power, using it to pump out deep mineshafts in particular. By the late 18th century, people started thinking about using steam engines to pull these carts up and down the tracks.

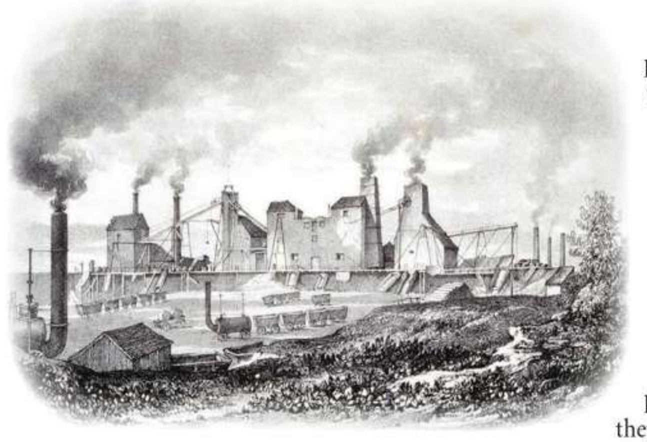
So the industrial revolution created the railways, not vice versa?

Yes, absolutely. Particularly, as I say, this need to move large volumes of heavy coal. The engineer George Stephenson began working in the collieries and the British standard rail gauge began as the gauge of a trackway in the north-east of England. Of course the railways did themselves give an enormous boost to the industrial revolution.

Was the development of the railways a collective process or more the result of geniuses such as the Stephensons?

It was a collective process. If you look at George Stephenson, he spent his early engineering career working in the coalmines of County Durham, where people were experimenting enormously with transport. He was right in the middle of that and was then able to enlarge on what he'd seen to build the Stockton and Darlington railway. This was the first serious railway in history. It was built primarily to transport coal to Stockton-on-Tees, doing exactly what trackways had been doing for years, but finally with a moving steam engine.

There was a massive hub of exciting developments going on in north-east England at the time. George Stephenson learned from them, perfected them, and added his little touch of genius as well, but it didn't burst fully formed out of Zeus's head like Athena. He was building on what had gone before.



GETTY

An 1822 lithograph of Hetton colliery, which was home to an early private railway. It was here that pioneering engineer George Stephenson cut his teeth

By 1840 there were 2,000 miles of track, but **by 1900 there were over 23,000 miles. It was extraordinary**

How much impact did the British landscape have on the development of railways?

Britain was the right country for railways to come to first. They were manageable propositions because all you had to do was transport things to the nearest water and, as an island nation, we're never very far from that. It was different when they brought railways into Canada, for example, where they had to build over vast distances with titanic sums of venture capital being required.

The Stockton and Darlington railway was about 26 miles long and the subsequent Liverpool and Manchester line wasn't a huge amount further. There weren't bewilderingly large distances involved. Also, the landscape, while being challenging, wasn't catastrophically difficult, which would be the case in other parts of the world.

Nineteenth-century Britain witnessed a railway fever. How was such rapid pace of growth achieved?

It was partly because an incredible virtuous circle was created. In the first 20 years of the railways' existence, iron and coal production tripled thanks to the added efficiencies provided by this new form of transport. The appetite for iron increased enormously too because you needed it to make trains and tracks.

There was also a huge, unexpected desire to ride on these trains. It was thought that early railways would be largely for coal and goods, but instead they proved overwhelmingly popular with people, passengers. This meant they were fantastically successful and they made money.

Some later railways ended up losing a vast amount of money, but early on there was simply a massive market for them. By 1840 there were 2,000 miles of tracks, but by 1900 there were over 23,000 miles. It was extraordinary and it shows that there was a lot of money in Britain at the time. There was (without wishing to sound like a Marxist) a kind of under-taxed elite looking for opportunities to invest the surplus value that they'd earned from textile mills, coalmines, iron foundries and things like that. This money was being ploughed into railways, which were very attractive investment opportunities.

Britain was a country where this was all doable. You could join up Birmingham and London or Liverpool and Manchester. These industrial hubs were being gradually connected and it created its own momentum.

Did the growth of the railways attract any opposition?

There was hostility from romantic poets and lovers of the countryside – although frankly that was brushed aside. There was more problematic opposition from a class of landed aristocrat who did not want railways to infringe their property rights. The original plan for the Liverpool and Manchester railway was actually defeated at the committee stage in the House of Commons because MPs thought it was a harebrained scheme and landowners didn't want members of the public crossing their land.

In addition, there was the extreme hardship suffered by many of the navvies, who could be paid well but also had high mortality rates and extremely tough lives. These people were virtually enslaved to the building of the railways because their salary was often used up buying food and alcohol and they ended up permanently indebted to the companies they were working for.

Then of course there were the slums that were cleared. People in north London were turfed out of their houses as the line from Birmingham came into the city, with

RAILWAY MILESTONES

1604
The first wagonway in Britain is constructed in the east Midlands by Huntington Beaumont to help transport coal towards the river Trent

1769
Scottish inventor James Watt patents a vastly improved steam engine. Together with partner Matthew Boulton he goes on to make crucial developments to steam power

1804
The world's first steam locomotive railway journey takes place in Penydarren in Wales. The vehicle has been built by Cornish engineer Richard Trevithick

1825
The Stockton and Darlington railway opens. Designed by George Stephenson, it is the world's first public railway

1829
George and Robert Stephenson's Rocket triumphs in the Rainhill Trials contest to find the best locomotive for the Liverpool and Manchester railway that will open the following year

1840s
Railway mania takes hold in Britain. By 1854 the network stretches over 6,000 miles

1853
The Crimean War begins. During the conflict, **Britain creates the Grand Crimean Central Railway** to aid with logistics

1914
The First World War sees railways playing a crucial role for the combatants in the transportation of food and other materials

1938
The British train Mallard sets a world record speed of 126mph. This remains a record for a steam locomotive

1948
Britain's railways are nationalised by the Labour government at a time when motor cars are beginning to supersede train travel

virtually no compensation. Charles Dickens writes about this memorably. It was felt that these people couldn't be allowed to get in the way of modernity and so they were left with nowhere to go.

Aside from the industrial and transport revolutions, how else did railways affect Britain?

They affected the country in virtually every way imaginable. What I find fascinating is simply the scale of it. This was one of the biggest building projects in history, more significant than the Great Wall of China, the Roman road system or the pyramids. One of the reasons it was so amazing was that, unlike those previous projects, it was built with private investors' money. It was the first democratic infrastructure boom and that is crucially important.

Not a penny of the funding for the early railways came from the public purse. It all came from private individuals, from the very rich right down to people giving a tiny part of their meagre paycheck because they wanted to become investors.

There was virtually no part of public life that remained unaltered. Railways changed the way people lived and worked, what they ate and even what they read. Penguin Books famously originated on a railway platform and WHSmith developed through railways. They give birth to the consumer revolution. Thomas Cook's travel agency was born on the railways. His first expedition was a temperance excursion and he went on to make vast amounts of money taking people to the seaside on trains.

However, the railways were also the enfant terrible of the 19th century because no one really knew where it would end. The railway mania eventually brought about the legendary financial collapse of 1866. It brought the British banking system to its knees. Not even Napoleon managed that.

As someone who has studied the navy and maritime history, I am also conscious of the way railways inverted our understanding of how the world works. Before the 19th century, human beings were largely a littoral species. We lived along coastlines and rivers. The great cities of the world like London, Paris, Beijing and New York were dependent on waterborne transport for their trade. The sea was a bridge linking one place to another and it was actually the land that was hostile. The Pennines were virtually impassable, but if you were in Newcastle you could sail to London no problem.

Yet, within a generation, the railways carved links to the landscape that forever changed the way we thought about our place in the world. Suddenly we saw the sea as slow

This project was more significant than the Great Wall of China, the Roman road system or the pyramids

and hostile and the land became the bridge. Entire countries and empires were carved out of this. It's not an exaggeration to say that modern Russia, the USA and Germany were created by railways. Without them, they wouldn't have been able to bind these vast, sprawling places into one state.

In the end, the railways actually undermined the legitimacy of the British empire. There was a new focus on land communication and so it became illegitimate for Britain to own these territorial possessions on the other side of the world, linked by water. America is just as much an empire as the British empire was, but because it's joined and you can travel over it by land there are far fewer questions about its legitimacy. These huge continental-sized nation states were developed – and Britain, in the end, simply could not compete.

Did the railways also create a new mentality in Britain?

They created a national mentality in many ways. Railways bind people together, enabling them to organise themselves nationally, quickly. Trade union activism and Chartism, for example, would have been impossible without the railways. Newspapers could travel around the country almost instantaneously and there was a huge movement of goods and people, which brought about a nation state where one had not existed previously.

Railways also introduced a national time. Various towns around Britain once had their own time zones, which was fine then, but when you have train timetables you need to have a national timetable. The time in London became the time everywhere else.

What did the railways mean for Britain as a military power?

They had a huge impact, starting with the Crimean War. They were vital in the First World War, where millions of tonnes of supplies were carried to the battlefield on rail. The early tanks, for example, couldn't possibly go over land all the way between battlefields, so they were all carried on the

Tourists travelling by train around Britain in 1876. Railways were originally intended to move goods, but passengers soon flocked to this new form of transport

backs of trains. Most of the men who were taken to France arrived at ports like Folkestone and Southampton by railway.

However, in the longer term a situation developed that, because landed transport became so much easier, Britain's naval domination mattered less. In the First World War. Germany was able to get material and supplies from the whole of Europe by rail in a way that Napoleon, for example, couldn't have done. Whereas France had been strangled by Britain's blockade, Germany had access to lots of the natural resources of Eurasia that could be moved using the railways. Britain's naval blockade did bite in the end, but it took quite a long time for this to happen.

When did the railway age come to an end and why?

It was partly because of under-investment during the Second World War and state ownership afterwards, and partly because of a fashionable obsession with the new motor car. There wasn't the rapid electrification of trains that would have reduced journey times and put up more of a fight against the encroaching of the car.

In many ways, of course, the railway age hasn't ended. There are still a vast number of journeys being made each year on Britain's railways and there's talk now of high-speed rail, which could give it a new lease of life. What's also interesting is the fact that the first motor cars were just trackless steam engines, so in a way I always see a smooth transition from the train to the motor car. H

Dan Snow is a historian, author and broadcaster. He has presented numerous BBC TV series including *Locomotion: Dan Snow's History of Railways* (2014), available on DVD

MOON SHAKER

Over 400 years on from the first lunar observations by telescope, **Christopher Lewis** considers how Galileo Galilei changed our view of the Moon and the heavens

The first giant leap towards landing on the Moon may have been taken over 400 years ago. From the summer of 1609 onwards, telescopic studies by Galileo Galilei and other astronomers helped to shatter the dominant medieval belief in the intrinsic separateness and inaccessibility, the literal other-worldliness, of the heavens and the Moon.

"The surface of the Moon," claimed Galileo, "is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and the other heavenly bodies) to be, but it is uneven, rough, and full of cavities and prominences, being not unlike the face of the Earth, relieved by chains of mountains and deep valleys."

The telescope, an instrument that Galileo did so much to refine, transformed our understanding of the Moon (and of the heavens in general) even more profoundly than the Apollo astronauts' first view of 'Earthrise' from the Moon helped change modern awareness of our fragile Earth.

From the moment that Galileo began to point his telescope towards the skies, it was only a small step further to imagine the Moon as another 'New World', ripe for exploration and colonisation.

It was on 13 March 1610 that the English ambassador to the Republic of Venice, Sir Henry Wotton (1568–1639), dashed off a letter to secretary of state Robert Cecil (1563–1612), enclosing a slim booklet, hot off the press:

"I send herewith unto His Majesty [James I] the strangest piece of news (as I may justly call it) that he hath ever yet received from any part of the world; which is the annexed book (come abroad this very day) of the Mathematical Professor at Padua, who by the help of an optical instrument (which both enlargeth and approximateth [brings closer] the object) invented first in Flanders, and bettered by himself, hath discovered four new planets rolling about the sphere of Jupiter, besides many other unknown fixed stars; likewise, the true cause of the *Via Lactea* [Milky Way], so long searched; and lastly, that the Moon is not spherical, but endued with many prominences… And the author runneth a fortune to be either exceeding famous or exceeding ridiculous."

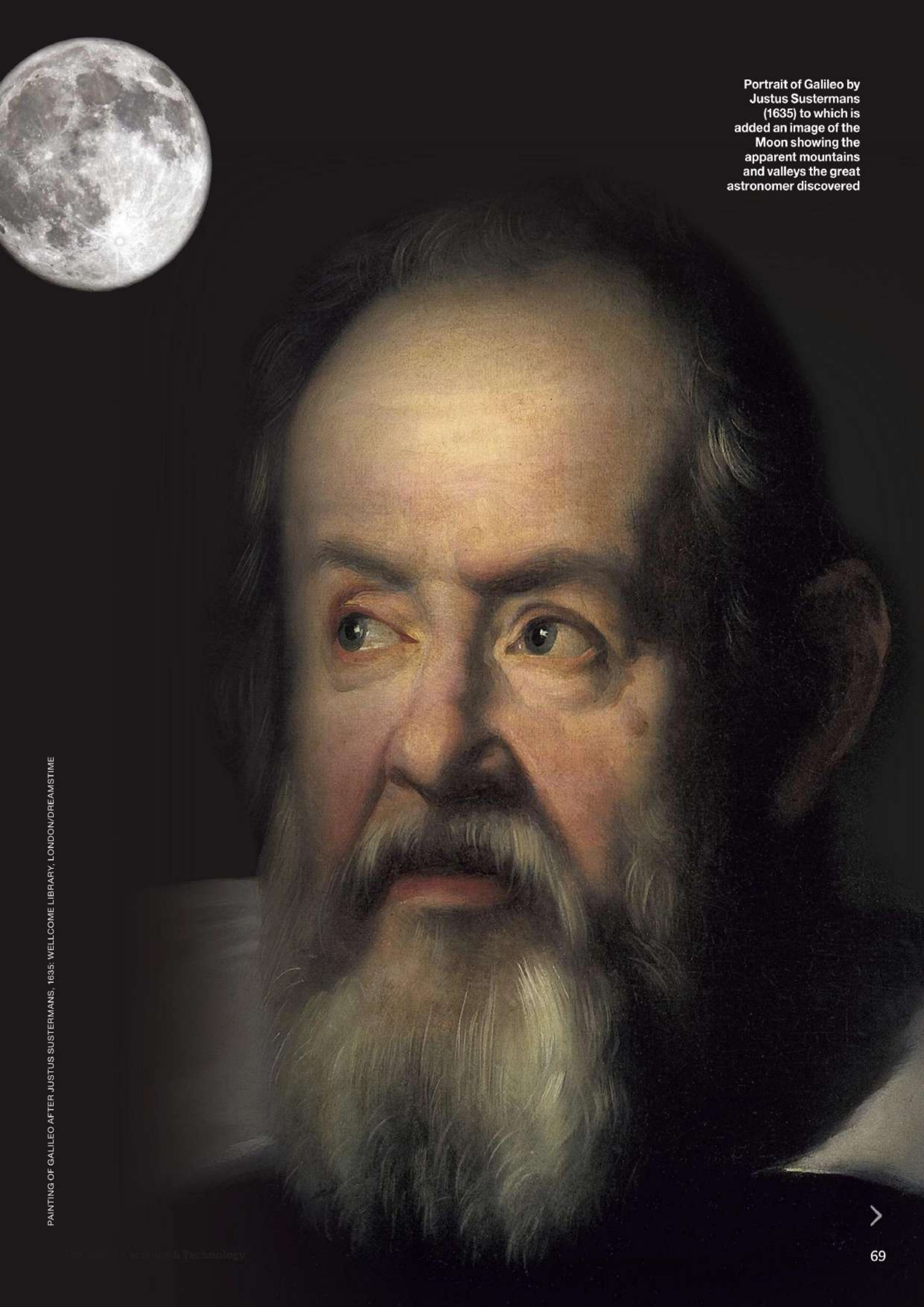
> Galileo wanted to prove that **the Moon was basically like the Earth**

Through the looking glass

The optical instrument was a telescope. The first clear, public claim to "a new invention", "a certain device by means of which all things at a very large distance can be seen as if they were nearby, by looking through glasses", was made in the Dutch Netherlands in September 1608. News of the invention spread rapidly throughout Europe and actual working examples of the 'spyglass' or 'optic tube' followed not far behind, arriving in Italy in the summer of 1609.

The "Mathematical Professor at Padua" referred to by Wotton was the 45-year-old well-respected academic Galileo Galilei. He had been improving the telescope design, and by the end of August 1609 he had developed a telescope that magnified some eight or nine times; by the end of the year he had a good eyeglass of 20x power.

The booklet Robert Cecil received was Galileo's *The Sidereal Messenger* (*Sidereus*



Portrait of Galileo by Justus Sustermans (1635) to which is added an image of the Moon showing the apparent mountains and valleys the great astronomer discovered

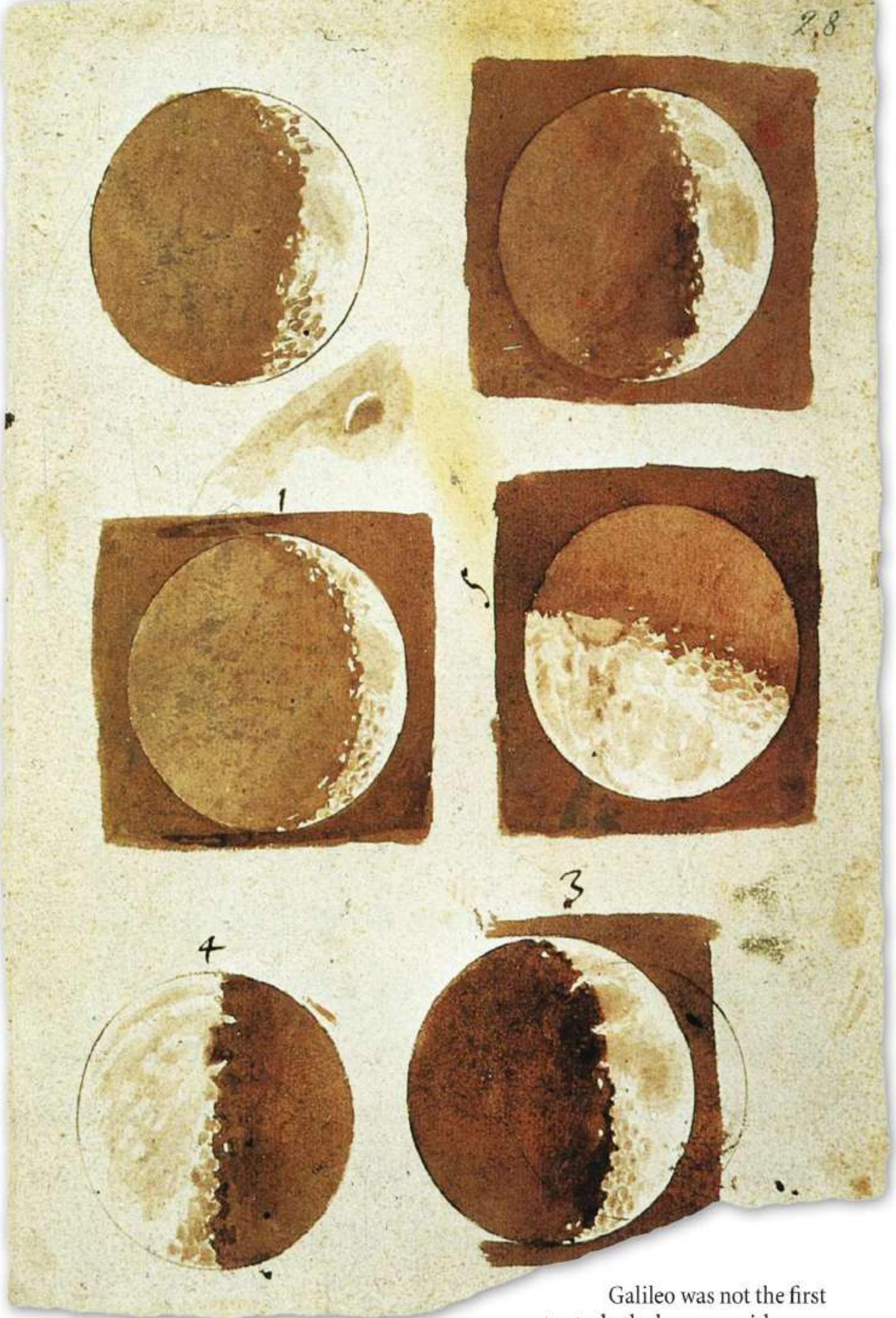
PAINTING OF GALILEO AFTER JUSTUS SUSTERMANS, 1635: WELLCOME LIBRARY, LONDON/DREAMSTIME

Galileo: a man of many parts

Galileo Galilei (1564–1642) was born into a respected but impecunious Florentine family. Quick-witted, sharp-tongued, good with his hands, fond of wine and women, he eventually settled upon a career in mathematics. He became professor of mathematics first at the university of Pisa and then, from 1592, at the more prestigious Venetian university of Padua. For the next 18 years, "the happiest years of my life", he devoted himself to the study of motion, magnets and many other topics, but he published very little.

His telescopic discoveries, however, earned him international celebrity and enabled him to return to Florence as "philosopher and chief mathematician" to the Medici grand duke of Tuscany. Cultured – he played the lute and wrote on Dante and Tasso – and clubbable, Galileo nevertheless made enemies as easily as friends. Academic and ecclesiastical opponents secured the banning of his cherished Copernican theory in 1616 and finally, after the publication of his great pro-Copernican *Dialogue Concerning the Two Chief World Systems*, engineered Galileo's conviction by the Roman Inquisition in 1633 for "vehement suspicion of heresy". Condemned to house arrest in Florence for the remainder of his life, Galileo finally turned to the completion and publication of perhaps his greatest work, *The Discourses on Two New Sciences* (1638), accurately describing the motions of falling bodies, projectiles and pendulums.

Ottavio Mario Leoni's portrait of Galileo



Some of Galileo's 1609 watercolour sketches of the moon. His observations led him to doubt that the Moon's surface was "precisely spherical"

Nuncius), which contained an account of his telescopic observations of the Moon and of the stars over the previous three or four months. Page for page, at least, this slim volume of some 40 quarto sides had a more immediate, widespread and profound influence upon our understanding of the cosmos and of man's place in it than any other work in the history of modern science. Galileo's discovery of four moons (Wotton's "four new planets") orbiting the planet Jupiter was certainly the most unexpected revelation – and the reason he had to rush into print in order to establish his priority – but it was probably his conclusions about the Earth-like nature of the Moon that had the greatest impact, at least upon the popular imagination.

Galileo was not the first to study the heavens with a telescope. The brilliant English mathematician Thomas Harriot (c1560–1621), for example, viewed the Moon through a telescope in the summer of 1609. Galileo observed the Moon systematically through at least one complete lunar cycle (from crescent new Moon, through full Moon, to waning crescent) in the autumn of that same year. Yet, in January 1610, his study of the Earth's satellite was interrupted by his sighting of four moons of Jupiter. Galileo's main objective now was to publish and claim priority for this utterly unprecedented discovery in *The Sidereal Messenger*. However, he also decided to include his drawings, descriptions and speculations about the Moon in the booklet.

Galileo was not interested in just mapping the Moon. He had a deeper scientific agenda: he wanted to prove that the Moon was basically like the Earth, and thus that there was no fundamental difference between the substance of the heavens and of the Earth.

ALAMY/GETTY

So how did he know that there were mountains and valleys on the Moon? It was not possible simply to 'see' that the surface of the Moon was not smooth, even with Galileo's excellent telescopes. His argument had to be more complex.

Galileo studied very carefully the slowly moving boundary (the 'terminator') between the bright, sunlit parts of the Moon and the dark part still in shadow. In the first place, he reported, "the boundaries of shadow and light in the Moon are seen to be uneven and wavy". Even more tellingly, "many bright points appear within the darkened portion of the Moon, completely divided and separated from the illuminated part and at a considerable distance from it. After a time these [points] gradually increase in size and brightness, and an hour or two later they become joined with the rest of the lighted part which has now increased in size." This, said Galileo, is exactly what happens on the Earth: "before the rising of the Sun, are not the highest peaks of the mountains illuminated by the Sun's rays while the plains remain in shadow? Does not the light go on spreading while the larger central parts of those mountains are becoming illuminated? And when the Sun has finally risen, does not the illumination of plains and hills finally become one?"

Galileo's ideas about the Moon were – and were meant to be – provocative. The understanding of nature, the "natural philosophy" taught in European universities at the time, was still largely dominated by the system of the ancient Greek philosopher Aristotle (384–322 BC). Aristotle had argued, very elegantly to be sure, that there was a fundamental difference between the nature and very substance of the heavens and of the Earth.

The Earth was stationary at the centre of the universe, surrounded – in the elaborated version of the medieval scholastics – by a nesting set of concentric spheres, each containing one of the seven planets, starting with the Moon. Everything below the sphere of the Moon, everything 'earthly', was subject to change, growth, decay. Everything in the sphere of the Moon or above was, on the contrary, perfect and unchanging. All celestial bodies had to move in perfectly circular orbits, and had to be perfectly spherical. This included the Moon.

Galileo's telescopic observations and arguments for the 'ruggedness' of the Moon directly challenged this key Aristotelian doctrine. Some academic philosophers – such as Galileo's own colleague (and drinking companion) at Padua, Cesare Cremonini (1550–1631) – simply declined to look through the telescope. Others sought to accommodate Galileo's conclusions, arguing, for example, that although the lunar mountains did exist, they were encased in a perfectly spherical outer layer of celestial crystal.

Would Christ have had to undergo **another Passion upon the Moon to save souls there?**

By the early 17th century, the Aristotelian cosmology was already under attack. The radical Sun-centred cosmology of Nicolaus Copernicus (1473–1543) was increasingly widely known and discussed. Galileo's telescopic discoveries did not definitely prove the Copernican theory, but they certainly undermined the established Aristotelian hypothesis.

Nevertheless, common-sense objection to the supposed motion of the Earth remained, understandably enough, very strong. Such discoveries as the moons of Jupiter or, later the same year, the phases of Venus – both quite difficult to observe without a good telescope – were undeniably influential among professional astronomers. In the popular imagination, however, it was the alleged Earth-like nature of the Moon that probably had the profoundest impact in launching the Earth into space to join the other planets in orbit around the Sun.

Mountains on the Moon

Galileo's suggestion that the Moon was rugged, mountainous, like the Earth, had further significant scientific and theological implications. Even viewed with the naked eye, the Moon has brighter and darker areas – hence the 'face' in the Moon. As Galileo himself remarked, therefore, "if anyone should wished to revive the old Pythagorean opinion that the moon is like another Earth, its brighter part might very fitly represent the surface of the land and its darker region that of the water".

Galileo himself was non-committal, but in the minds of many readers this promptly suggested plants and animals, and maybe rational, even human, inhabitants. But, as Galileo's ecclesiastical friend Giovanni Ciampoli (c1590– 1643) reminded him, this was no idle speculation, for it raised the question "how these [human inhabitants] can be descended from Adam, or how they can have come off Noah's ark, and many other extravagances you never dreamed of". Would Christ, for example, have had to undergo another Passion upon the Moon to save such human souls as lived there?

Have we not lately in the moon,
Found a new world, to th'old unknown?
Discovered seas and lands Columbus
And Magellan could never compass?
Made mountains with our tubes appear,
And cattle grazing on them there?
(Samuel Butler, *Hudibras*, 1664)

For many people, theological technicalities were less important than the exciting parallels with the ongoing voyages of discovery on Earth: were there new worlds to explore in the solar system comparable to the New World on Earth? Galileo himself was often compared, especially in poetry, to a new and greater Columbus. A colonial initiative was never far behind. "Do but consider the pleasure and profit of those later discoveries in America," Bishop John Wilkins urged his readers, "and we must needs conclude this [world in the Moon] to be inconceivably beyond it." In coming years, the Moon was indeed claimed in turn by Spaniards, Italians, Dutch, and many others beside the British.

Gradual technical improvement in telescope design produced a new generation of lunar map-makers. The *Selenographia* (1647) of Johannes Hevelius (1611–87) set the cartographic standard for almost the next 150 years. It was the *Almagestum Novum* (1651) of the Jesuit Giovanni Riccioli (1598–1671), however, that established the basic modern system for *naming* lunar features. Without Riccioli, the Apollo astronauts would have stepped out not into the Sea of Tranquillity but, instead, into 'the Black Sea' or perhaps even 'the Belgian Sea'.

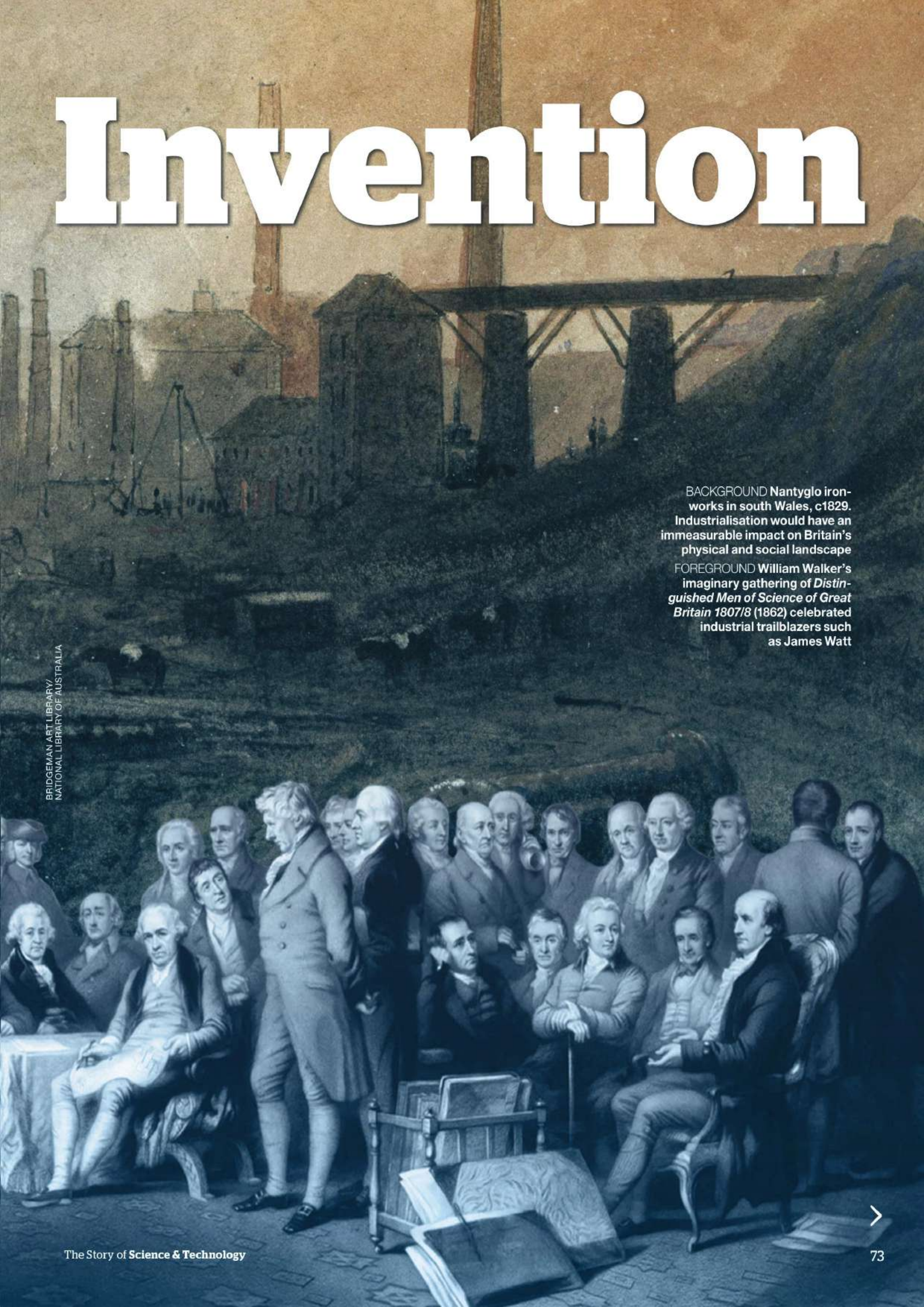
The telescope helped to bring the Moon (and the heavens) down to Earth, and demanded the same unified physics for the celestial and earthly realms. Without that unity, Newton's universal mechanics and gravitation would have been unthinkable. Plotting a trajectory to the Moon would have been inconceivable outside the myths of Orpheus and the poetry of Dante. Such a journey would have crossed the boundary between the mortal world of man and the eternal world of spirit. Without Galileo's telescope to make the Moon into another Earth, the Apollo astronauts could never have set off. H

Christopher Lewis is an affiliated scholar in the department of history and philosophy of science at Cambridge University, studying the life and times of Galileo

Heroes of

The industrial revolution brought insecurity and squalor to many, but, as **Christine MacLeod** explains, many of the great inventors and industrialists of the 19th century – particularly those in steam power – were lionised and honoured in their lifetimes

Invention



BACKGROUND **Nantyglo iron-works in south Wales, c1829. Industrialisation would have an immeasurable impact on Britain's physical and social landscape**

FOREGROUND **William Walker's imaginary gathering of *Distinguished Men of Science of Great Britain 1807/8* (1862) celebrated industrial trailblazers such as James Watt**

BRIDGEMAN ART LIBRARY/ NATIONAL LIBRARY OF AUSTRALIA

A statue of James Watt in Glasgow. By 1834, Glasgow boasted three statues of Watt

The prime minister, Lord Liverpool, told parliament in 1820 that "England was indebted for its present greatness" to men such as James Watt, Matthew Boulton and Richard Arkwright. It was an astonishing statement from a prime minister whose cabinet included the hero of Waterloo and nation's darling Arthur Wellesley, first Duke of Wellington. No less astounding, he made it to a body still largely composed of landowners, which in 1815 enacted the Corn Law to protect Britain's agriculture at the probable expense of her industry. Yet, this was not the first time that Liverpool had identified "the machinery and mechanical inventions of this country" as the upcoming source of national wealth and power, and in 1824 he would chair a meeting to launch a subscription for a monument in Westminster Abbey to James Watt, who had died in 1819.

Others' rhetoric on that occasion hugely exaggerated the significance of the steam engine and hymned Watt, its 'inventor', as the true victor of the Napoleonic wars. If their analysis of steam power's importance for British industry was premature, like Liverpool's it demonstrated their awareness of the tectonic change occurring in Britain's economy and its role in funding Wellington's victory. Their erection of a 'colossal' statue of Watt among the abbey's aristocratic tombs symbolised this change at the same time as the Reform Act of 1832 recognised the challenge it presented to the aristocracy's hold on power. It also inaugurated a tradition of commemorating inventors and engineers, such as the recent tercentenary of the death of Abraham Darby, inventor of the coke-smelting process for iron making at Coalbrookdale or the bicentenary of the death of Matthew Boulton in Birmingham, where he and Watt established their steam-engine business.

From William Blake's powerful image of 'dark satanic mills' to Arnold Toynbee's coining of 'the Industrial Revolution' only to condemn it, the loud cries of industrialisation's critics and victims have suppressed the acclamations with which many 19th-century Britons greeted it. The first generation of professional economic historians, aghast at the persistence of poverty in the midst of Victorian prosperity, took their cue from investigators of social deprivation such as Henry Mayhew and Friedrich Engels. Thus Toynbee's *Lectures on the Industrial Revolution in England* (1884) together with the publications of JL and Barbara Hammond and Sidney and Beatrice Webb established a catastrophist history of industrialisation that still dominates school textbooks and popular histories, despite simultaneously evincing pride in its technical achievements.

Familiarity with the poetry of Wordsworth, the fiction of Dickens and the illustrations of Gustave Doré deepens this sense of gloom and regret. Postwar economic historians' more positive assessments of industrialisation, with their emphasis on long-term economic growth, higher standards of living and extended life expectancy, have done little to disturb our ingrained belief that the industrial revolution was almost universally deplored by those who lived through it.

Undoubtedly, many workers deskilled by new technologies lost their livelihoods, many were made homeless by railway construction, and many lives were shortened by scandalous working conditions and jerry-built, unsanitary housing. Yet, numerous others benefited; they saw in the smoke from factory chimneys not air pollution but evidence of prosperity. Industrialisation demanded new skills, especially in the engineering and metal-working trades: to build and maintain machinery, operate boilers, drive locomotives, mine coal and tend spinning-mules and power-looms. Such men could command high wages, belong to a trade union, maintain a family and aspire to education and the vote. They believed it was their skills that were making Britain great and they admired the inventors who had set it on this industrial path to wealth and power, especially the pioneers of steam.

The **cries of industrialisation's critics** have suppressed the acclamations with which Britons once greeted it

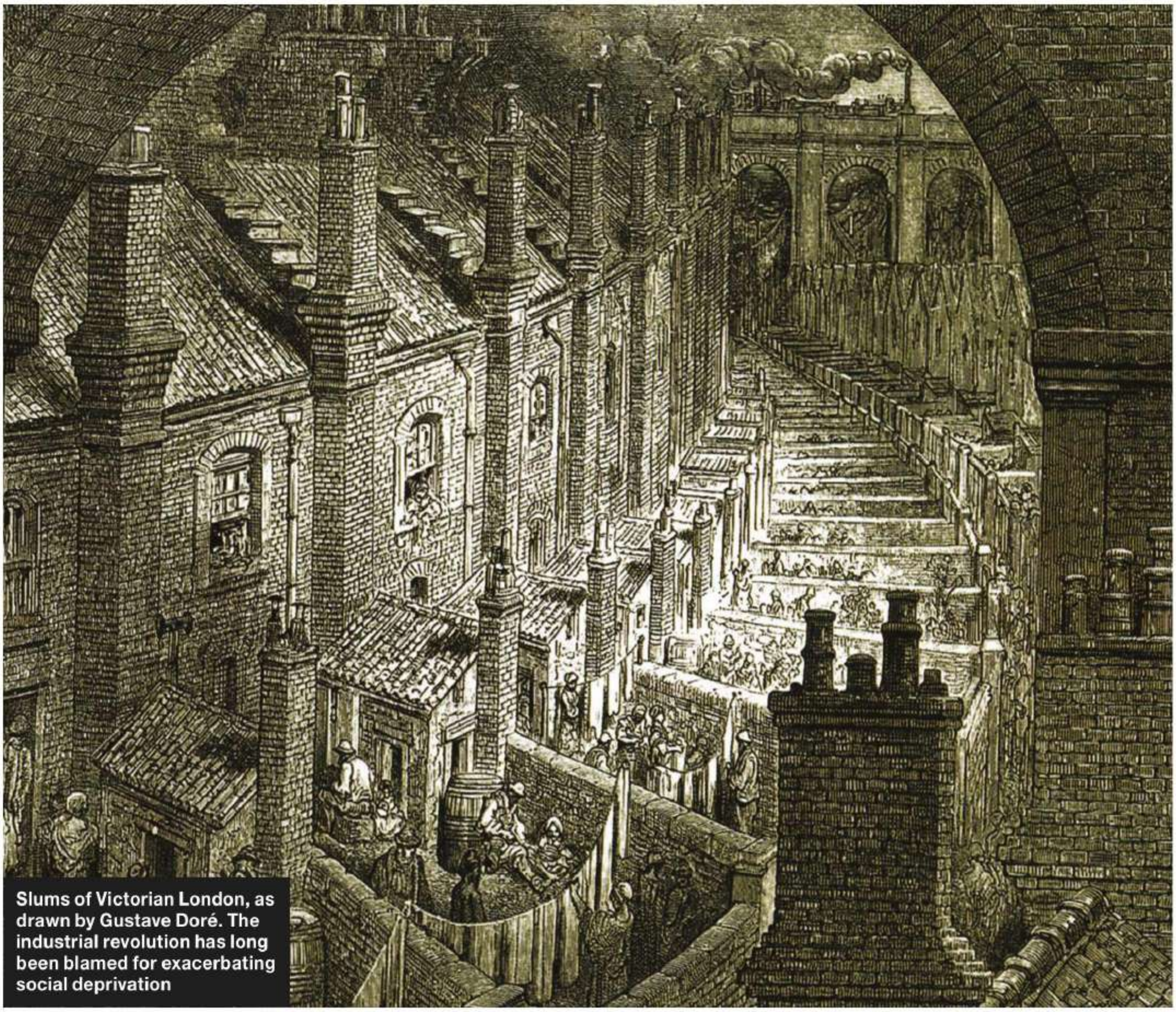
Watt was their first hero. An instrument maker by trade, he posthumously breached the national pantheon where military figures jostled a few cultural lions – Shakespeare, Milton, Bacon and Newton. The second was George Stephenson, another working man, whose engineering feats had transfixed public attention ever since the first train ran on the Liverpool to Manchester railway in 1830. During the 1840s and 50s, his son Robert Stephenson, Isambard Kingdom Brunel and Joseph Locke ('the railway triumvirate') held centre stage, but in the wake of their coincidental deaths in 1859–60, loyalty to the older generation was reasserted. By then, Watt and George Stephenson were celebrated nationally, locally, and by the engineering trades and professions (Stephenson was elected first president of the Institution of Mechanical Engineers, 1847–48). Their biographies provoked emulation and their achievements were entered into the history books, as monarchical politics began ceding several pages to 'the rise of manufactures'.

What's Watt?

In 1824, when liberal Tory members of Liverpool's cabinet joined with moderate whigs, leading fellows of the Royal Society and well-heeled manufacturers to commemorate Watt, the radicals realised they had missed a trick. William Cobbett, one of 19th-century England's leading champions of political reform, bellowed: "WHAT'S WATT? I, of late, hear a great deal about IT; but, for the life of me, I cannot make out what this Watt IS' (Cobbett's *Political Register*, 24 August 1824). Cobbett's feigned ignorance belied his anxiety that Watt's reputation was being hijacked by the 'cotton lords' to the detriment of the slaves of both plantation and factory. He proposed a cast-iron statue of 'the great mechanic' with panels on its plinth illustrating their distress, the "effects of the system which Mr Watt's inventions have established among us".

By contrast, a subscription of £6,000 bought a huge block of marble and the talents of sculptor Sir Francis Chantrey: Watt's seated figure in Westminster Abbey wore academic robes, a 'philosopher' rather than an engineer. Lord Liverpool made subscribing fashionable when he persuaded George IV to give £500. The Boulton family donated £500 and other close friends £50 to £100

BRIDGEMAN



Slums of Victorian London, as drawn by Gustave Doré. The industrial revolution has long been blamed for exacerbating social deprivation

each, but most subscriptions were of five to ten guineas, from people unknown to Watt. As Cobbett predicted, grateful 'cotton lords' sprang to the cause.

Manchester, despite having no direct connection to Watt, contributed £1,100. Without fast-flowing rivers, the city's expansion since the 1780s had depended entirely on Watt's rotative steam engine. By the 1820s, 'Cottonopolis' (as Manchester was dubbed) was a bastion of free trade and provincial science, and saw in steam power both the opportunity for worldwide shipping services and proof of the utility of scientific investigations. In 1857, the city would inaugurate its own monument to Watt in Piccadilly Gardens, subscribing £1,000 for a copy of Chantrey's statue by William Theed the Younger.

Already in 1824, Glasgow, the other centre of Britain's cotton industry, preferred to go its own way, raising £3,500 to commission Chantrey to dignify George Square with a similar bronze statue (see above left). As the Lord Provost told a large public meeting, Glasgow was proud to be "the city which gave birth to those mighty efforts of his genius". It had, after all, been while repairing Glasgow University's model Newcomen engine that Watt conceived of the fuel-saving separate condenser.

A new Newton

However, popular admiration for Watt extended well beyond the cotton industry and the professoriate. Not only did numerous artisans and tradesmen subscribe, but substantial sums were collected in a dozen (mainly engineering) workshops – impressed perhaps by the tutor at Anderson's Institution, Glasgow, who stated that Watt had rescued "the term Mechanic… from opprobrium, and [rendered] it as honourable a title as any man could possess", or the chemist Andrew Ure, who declared that Watt "has done for the earth what Newton did for the Heavens" (*Glasgow Mechanics' Magazine*, 4 December 1824 and 1 January 1825).

Down the Clyde, Greenock proclaimed its status as Watt's birthplace with yet another commission for Chantrey, prompting James Watt Junior to donate a library to the town, to shelter the marble statue. Edinburgh, torn between its Scottish and its British identities, debated whether or not to cede the honour of Watt to Westminster Abbey, and decided not. It collected over £1,250 but that was insufficient to achieve its ambitious plans. Consequently, it was 1851 before the Watt Institution and School of Arts funded a statue by Peter Slater for its new building in Adam Square.

By then, Watt's memory was regularly toasted both at trade unionists' and professional engineers' dinners, verses were written in his honour and his image appeared on unions' membership certificates. Thomas Wright described how a new apprentice would be interrogated by his peers, "as to his designs about becoming the Stephenson or Watt of his day: in a word to 'taking his measure'". In 1868, when Birmingham commissioned a statue to stand in front of the town hall, *The Times* remarked that "no small share was contributed by the working men of Birmingham". This time Watt was dressed in everyday clothes, standing next to a steam-engine cylinder. Newly enfranchised

Local heroes: celebrating six innovators

Statues and celebrations were de rigueur in the hometowns of the great industrial trailblazers

James Watt Glasgow

By 1834, Glasgow boasted three statues of Watt, two the product of public subscriptions, one the gift of James Watt Junior to the university. Between 1864 and 1906, five more statues were privately commissioned for the city's buildings. Glasgow's engineering societies hold an annual James Watt Anniversary Dinner; Glasgow University named its engineering laboratories after him, and in 1919 marked the centenary of his death by establishing two James Watt chairs of engineering, funded chiefly by Scottish engineers.

Matthew Boulton Birmingham

Boulton was at least as prominent in life as Watt, yet has posthumously been overshadowed. His entrepreneurial and inventive talents (especially his coining machinery, supplied to numerous European mints) would not be so well remembered today without Watt's steam engines. However, in 1956 Birmingham commissioned William Bloye's bronze *Conversazione*, in which the life-size figures of Boulton, Watt and William Murdoch discuss an engineering drawing. Boulton's home, Soho House, was opened in 1995 as a museum to him and the city also marked the bicentenary of his death in 2009.

The statue of Boulton, Watt and Murdoch in Broad Street, Birmingham

George Stephenson Newcastle-upon-Tyne

George and his son, Robert, were born on Tyneside and lived most of their lives there. The city's chief monument to George, erected in 1862, stands in Neville Street, appropriately close to the railway station. Some 70,000 people attended the inauguration festivities. In 1881, Newcastle celebrated the centenary of his birth even more grandly, with exhibitions, lectures, fireworks, a public breakfast to launch a 'Stephenson scholarship' fund and a procession of 16 locomotives from the central station to his birthplace at Wylam and back. Stephenson's birthplace (pictured above) is now in the care of the National Trust.

Abraham Darby Ironbridge

Born in Wren's Nest (Worcestershire) in 1678, Darby's prime association is with Coalbrookdale, where in 1709 he reputedly invented the smelting of iron with (coked) coal, and founded a major iron-making dynasty. The greatest monument to his achievements is the world's first iron bridge (pictured below), which has spanned the Severn Gorge at Coalbrookdale since 1779. Its inter-locking parts were cast in the Darby foundry, which by then had passed to his grandson, Abraham Darby III (1750–89). Since 1967, the Ironbridge Gorge Museum Trust has preserved the remains of industry in the gorge by establishing several highly innovative museums.

Samuel Crompton Bolton

The inventor of the (unpatented) spinning mule, Crompton died poor and unremarked in 1827. Posthumously he rose to fame, thanks initially to Gilbert French, a local antiquarian who, in 1859, published his biography. French's championing of Crompton inspired Bolton's workers to fund the bronze statue by William Calder Marshall, unveiled in the town in 1862. Bolton's centenary celebrations in 1927 included a children's pageant, which culminated in a song, inviting *"Ye Men of Crompton's Native Town… [to] Sound his Fame Across the Earth"*. Crompton's childhood home, Hall i' th' Wood is now open to the public.

Richard Trevithick Camborne

Allegedly saved from a pauper's funeral by his fellow workers in Dartford (Kent) in 1833, Trevithick was rediscovered when the Institution of Civil Engineers launched a subscription for a memorial window in Westminster Abbey to mark the 50th anniversary of his death. That window now features Cornish symbols and four angels, each holding a drawing of a Trevithick invention, including 'Railway locomotive, 1808'. On Christmas Eve 1901, Camborne celebrated the centenary of the steam road locomotive, the *Puffing Devil*'s journey through the town.

A 'Trevithick Day' celebration still takes place annually. Since 1932, a statue of Trevithick has stood in front of the town hall.

An 1816 portrait of Cornish engineer Richard Trevithick

ALAMY/DREAMSTIME/NATIONAL TRUST-GEOFFREY FROSHT/PHIL HOSKEN/BRIDGEMAN

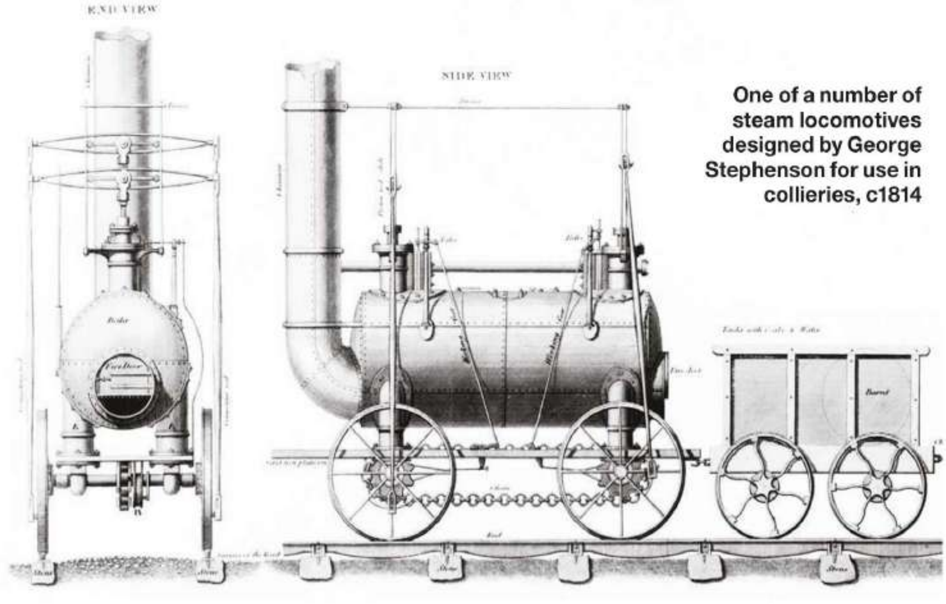
under the 1867 act, artisans reclaimed Watt; he was as much their figurehead then as he had been their employers' in 1832.

As the engineer William Fairbairn remarked in 1836, Watt had "given a freedom and impetus to the inventive genius of his country". From the mid-1820s the status of inventors improved. Demands for a more efficient patent system prompted the first parliamentary inquiry into its operation in 1829, although it was another 23 years before its statutory reform. The balance of litigation also swung in patentees' favour, as the courts began to sympathise less often with those who infringed a patent. Promoters of steam transport also took heart. *The Morning Chronicle* (18 August 1824) crowed that canal proprietors' attempts to block railway schemes had been doomed from the moment "the prime minister and his coadjutors" met to celebrate Watt.

Publishers rushed out books to explain the technology of steam to a lay audience, often prefaced by a history of its development and an encomium on its wealth-creating and civilising powers. In the 1830s, boosted further by excitement over railways, steam power began to star in less specialised works, as both critics and celebrants of industrialisation focused on its role.

Again there was a tendency to exaggerate its importance: water power remained Britain's chief source of mechanical energy until the mid-19th century. Yet this didn't stop the Board of Trade statistician George Porter declaring that the steam engine and cotton machinery had produced "almost magical effects upon the productive energies of this kingdom" (*The Progress of the Nation*, 1836–43). John Wade, a radical journalist, considered Watt's engine to be "the foundation… for the prodigious advance in wealth and population which marked the reign of George III", a development of greater significance than any war or other political event (*History of the Middle and Working Classes*, 1833). Whig historians, such as James McCulloch and Lord Macaulay, whose explanation of Britain's commercial superiority was grounded in the 1689 Bill of Rights, now saw in steam power the principal agent through which this constitutional freedom was transmuted into wealth and international dominance.

While Engels warned German readers in 1844 that the steam-powered cotton industry had produced a horrific "industrial revolution" which was threatening political upheaval, most liberal commentators enjoyed equally high expectations of steam's peaceful transformative powers. It would speed commerce, Christianity and civilisation to all corners of the globe, promote free trade and mutual understanding, and, in the words of Lord Macaulay, "bind together all the branches of the great human family". This would maintain Britain's near monopoly over global trade in manufactures, especially since, should there be a 'family' argument, steam ships and railways would hasten the deployment of troops worldwide.



One of a number of steam locomotives designed by George Stephenson for use in collieries, c1814

Steam's transformative powers would speed commerce, Christianity and **civilisation to all corners of the globe**

The outbreak of the Crimean War in 1854 laid bare this unresolved tension in liberal values. While refuting the easy assumption that free trade necessarily entailed global peace, the war offered inventors and engineers an opportunity to serve the military state. For some, the contribution of engineers such as William Armstrong and Joseph Whitworth to the development of more powerful weapons demonstrated modern society's dependence on inventors, who consequently merited greater reward and recognition. The author of an article in *The Builder*, in December 1860, was explicit:

"When we reflect how powerless the efforts of the wisest general, or the bravest soldier, would be against those modern cannon and rifled muskets and other means which science has brought into use… it would seem the time has arrived when equal honour should be shown to peaceful benefactors of the state, with that which has been shown to the mighty men of the sword."

Distinguished men of science

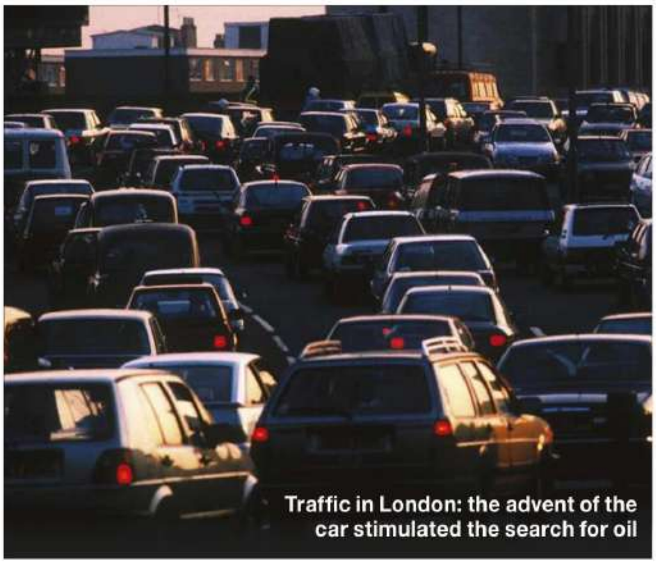
By contrast, the *Mechanic's Magazine* urged "that our engineers may, ere long, be permitted to return to their legitimate occupations, and learn the arts of war no more" (27 September 1861), while *Punch* regularly sniped at William Armstrong, in 1868 dubbing him 'Lord Bomb'.

The choice of subjects for biographies, group portraits or decorative busts for new buildings now often reflected these opposing stances. In William Walker's imaginary gathering of *Distinguished Men of Science of Great Britain Living in AD 1807/8* (1862), with Watt at its centre, there were some 33 inventors and 7 civil engineers, and only 11 scientists unconnected to any invention. In this engraving, begun during the Crimean War, military and commercial advances were inextricably linked. The inventions and discoveries of "these gifted men", declared Walker, "…are the grand Main-Springs of our National Wealth and Enterprise".

The Victorians composed the first grand narrative of the industrial revolution, identifying it with "the rise of manufactures" during the reign of George III (1760–1820). Whether they saw it as triumph or tragedy, it was indubitably a quick and dramatic event (a 'revolution'), an exclusively British phenomenon and the product of new technologies (principally steam power and cotton machinery) invented by a few dozen inspired men.

Constantly battling this stereotype, modern historians contend that industrialisation was a more complex and gradual development, with long roots stretching back into medieval institutions and out through Europe and beyond, to Asia and European settlements in the New World. While new technology undoubtedly played an important role, it too is better understood in a broader context, as the product of society's changing needs and wants, rather than as an independent force for change.

Will we celebrate the industrial revolution in the future?


Traffic in London: the advent of the car stimulated the search for oil

While the reputation of the industrial revolution has gone from triumph to tragedy and back again, the positive postwar assessment may be on the verge of crumbling in the face of current anxieties about climate change.

The long-running 'standard of living debate' has centred on the experience of those who bore the brunt of mechanisation and urbanisation between 1760 and 1830. Scarcely anyone has doubted the long-term benefits for industrialised countries: life expectancy has doubled since the 18th century, thanks not least to massively reduced infant mortality; ordinary people enjoy material comforts previously available only to the very rich, as well as free education, extensive leisure and a safety net of health services and social welfare benefits. Few have hitherto explored the costs to the environment.

The figure of 280ppm is regularly quoted as the concentration of carbon dioxide in the atmosphere prior to the industrial revolution. That is, for every million molecules in the atmosphere before 1760 approximately 280 were carbon dioxide. With 2009's figure peaking at 397ppm, as measured at the Zeppelin research station in the Norwegian Arctic (*The Guardian*, 28 April 2009), and now rising at an unprecedented 2–3ppm per year, we appear to have little time to prevent levels reaching the 450ppm maximum advised by climate scientists. It is time to reinterpret the industrial revolution in the light of this serious threat to our way of life, even to our survival as a species.

> Few have hitherto explored the costs of the industrial revolution **on the environment**

What marks industrialisation out from all previous periods of economic growth is that it has allowed two previously incompatible phenomena to co-exist: increasing population and continuous improvements in the standard of living. Without such sustained economic growth, human populations had grown at their peril – falling foul of the so-called 'Malthusian trap', in which numbers were cut back by famine, war or disease (induced by food shortages).

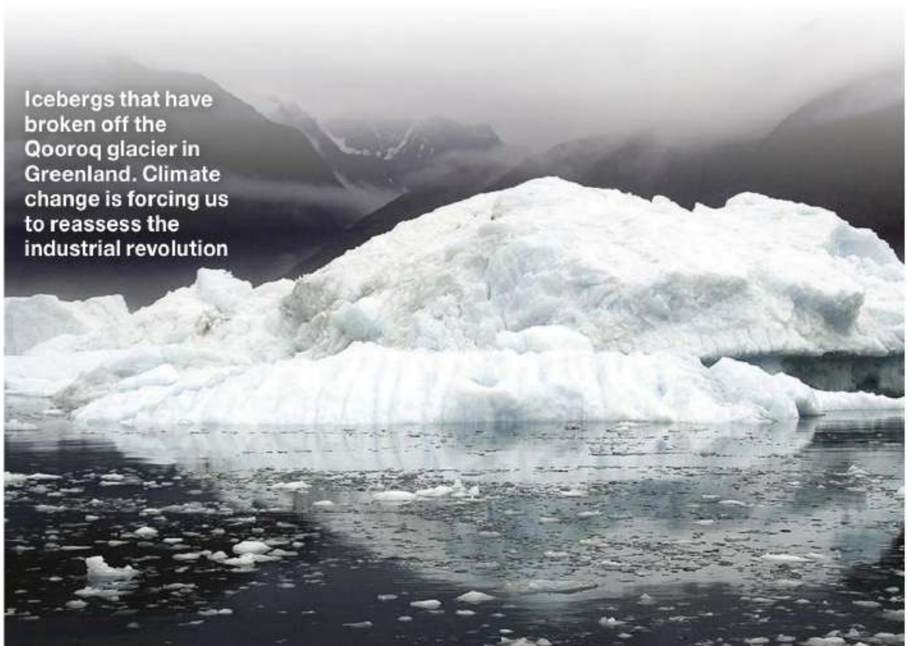
From the mid-18th century, Europeans escaped the 'Malthusian trap' by two principal routes. First, they mined fossil fuels in huge quantities. With timber stocks rapidly depleting, they turned to burning coal in industrial processes and in the steam engines that replaced water power and horse-driven transport. By 1890, the car's introduction was stimulating the search for oil, and electricity generation was stoking the demand for coal.

Second, they crossed the oceans to settle on other, much less densely populated continents. Here they introduced new species, crops and techniques into farming, often employed slave labour, and tended to grow in numbers and wealth even faster than before. International trade flourished under the stimulus of specialisation: Europeans began importing vast quantities of food and industrial raw materials in exchange for manufactured goods.

By 1900, humanity's impact on the atmosphere was still relatively slight: global population was only 1.6 billion, industrialisation was confined to western Europe, the United States and Japan, and even there levels of consumption remained modest. It was the long, post-1950 economic boom that triggered a steep and accelerating rise in greenhouse gas emissions.

Soon industrialisation and urbanisation became global phenomena, and growing wealth entailed much higher levels of personal consumption, mobility and international trade. This accelerated the demand for energy, and dietary changes that have led to more intensive rearing of (methane-emitting) livestock and extensive deforestation consequent on growing their feedstuffs.

A global population of over seven billion multiplies humanity's impact – and none are having a greater effect on the climate than the one billion of us who are the industrial revolution's chief beneficiaries. H


Icebergs that have broken off the Qooroq glacier in Greenland. Climate change is forcing us to reassess the industrial revolution

Christine MacLeod is emeritus professor of history at the University of Bristol, and the author of *Heroes of Invention: Technology, Liberalism and British Identity, 1750–1914* (Cambridge University Press, 2010)

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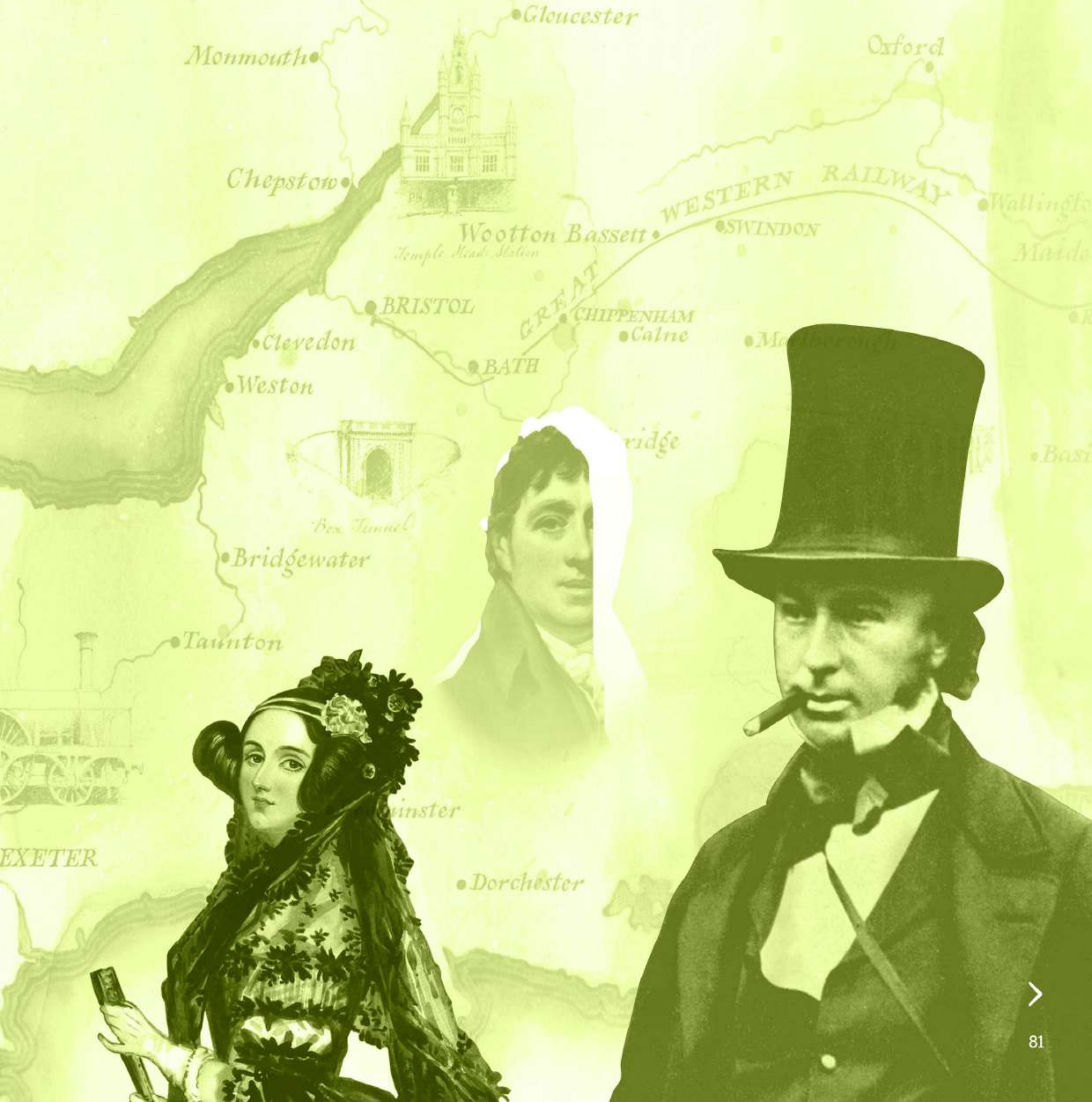

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ADA LOVELACE A VISIONARY OF COMPUTING

Born in 1815, Lovelace's fascination with science and maths defied the expectations of her gender and she is now considered to be one of the most important figures in the early history of the computer. **James Essinger** explores her life and legacy

One of many figures in the history of science whose work was only properly appreciated posthumously, Ada Lovelace (1815–52) is regarded as one of the most important figures in the early history of the computer. Not only was she a woman working at a time when men dominated science and maths, she also had a farsighted insight into the potential of computers.

Nowadays usually known as 'Ada Lovelace', Augusta Ada King-Noel, Countess of Lovelace, was born Ada Byron on 10 December 1815, the only child of poet Lord Byron and his wife Anne Isabella Milbanke, usually known as Annabella. Byron and Annabella were married on 2 January 1815 but by early 1816 Annabella had grown sick of her husband's infidelities and the appalling financial pressures of their married life. She left Byron, taking Ada with her to her parents. Ada never saw her father again.

From her childhood, Ada had a fascination with mathematics. This was encouraged by her mother, terrified Ada might grow up as feckless and purposeless as Byron had been, or be destroyed by an over-active imagination. The young Ada became close to obsessed not only by mathematics but also by science. While living in Canterbury in 1828, she conceived the idea of building a steam-powered flying machine and spent hours trying to work out how it might operate.

Despite Ada's yearning for a life of the mind, she was directed by her mother to follow a conventional upper middle class upbringing. By this point Lady Byron was one of the wealthiest women in Britain, and had the influence and power to ensure Ada did exactly as she pleased. In

Shown as a society lady in this 1840 painting, Ada's real passion was for science and maths

1835 Ada married a pleasant but not especially intellectual aristocrat, Lord William King, who in due course inherited the title of Earl of Lovelace. He was devoted to Ada and admired her greatly. He once reportedly remarked: "What a general you would make."

A pioneering friendship

By this time Ada had also encountered another man who made a huge impression on her, on both a personal and intellectual level. This was Charles Babbage, who she met on 5 June 1833 at a party. Ada was fascinated by Babbage and his plans to build a cogwheel calculating machine, which he called the Difference Engine. Babbage was surely flattered by the attention from a famous young lady – Ada's fame stemmed from her father, and she was something of a celebrity. Babbage invited Lady Byron and Ada to visit his home on Dorset Street, near Manchester Square in London, to see a completed model he had made of his Difference Engine (a working model one-seventh of the full-size machine, the whole of which Babbage never managed to complete). Ada was deeply impressed. She and Babbage became friends, though due to the fact that Ada was only 17 when they met, in the early days they usually met only when Lady Byron was present.

In 1834, Babbage began working on an even more ambitious machine, which he called the Analytical Engine. This was essentially a general-purpose programmable digital computer that used cogwheels operating in base 10 (our everyday mathematical numbering system that uses decimal numbers), rather than electronic components operating in binary. Otherwise, it featured most of the logical components of a modern electronic computer. These included memory, storage and programming, for which Babbage borrowed the idea of using punched cards from the programmable Jacquard Loom (a programmable loom first demonstrated in 1801, which could weave any pattern). It even featured security measures to warn the operator when they made a mistake.

Lovelace was even more fascinated by the Analytical Engine than by the Difference Engine. Yet while Babbage's plans for the Analytical Engine never got beyond the design stage, they include 2,200 notations and about 300 design drawings. For a long time, many modern commentators, typically male computer scientists, were scathing about Lovelace's contribution to Babbage's work, regarding her at best as merely someone who was helpful in publicising his efforts. Babbage called her his 'interpretess' – clearly that was how he regarded her contribution.


GETTY

Lovelace saw this portion of Difference Engine No. 1 – an early design from the 1820s – at Babbage's home in London

Ada clearly had insights into the Analytical Engine that Babbage seemingly lacked

Yet modern research has made it clear that Lovelace's contribution to the thinking at the heart of the prehistory of the computer was enormous. In 1843 she translated a paper on the Analytical Engine from French, written by an Italian scientist and future prime minister of Italy, Luigi Federico Menabrea. Lovelace went far beyond merely translating this paper – she wrote around 20,000 words of her own Notes that discussed the engine's potential. Her translation and Notes were published under her initials, AAL.

While it is clear Babbage helped Lovelace with some of the technical material in her Notes, theories that Babbage wrote most of the Notes himself have now been discredited. This is partly because linguistic analysis shows that the voice the Notes were written in was very much Ada's, but also because Ada clearly had insights into the Analytical Engine that Babbage seemingly lacked. Babbage saw it as a brilliant machine for doing mathematics, which it certainly was, but, there is no clear evidence that he ever saw it as anything more.

Lovelace's Notes, on the other hand, reveal that she regarded the machine as something that could not only enact calculations, but also carry out all kinds of processes that could govern all kinds of applications. She famously remarked that the "Analytical Engine weaves algebraical patterns just as the Jacquard Loom weaves flowers and leaves". This brilliant insight is an important part of Lovelace's contribution towards the early history of the computer. She called her own particular brand of thinking about science "poetical science", and also recognised that the Analytical Engine could even compose music if properly set up to do so. As she wrote: "Supposing that the fundamental relations of pitched sounds in the science of harmony and of musical composition could be expressed and adapted within the Analytical Engine, it might compose elaborate and scientific pieces of music of any degree of complexity or extent."

Ada Lovelace's legacy

On 27 November 1852, Ada died from cancer, most likely of the uterus. She was only 36, the same age at which her father had died. She now lies next to him in the sealed Byron family tomb in St Mary Magdalene Church, Hucknall, in Nottinghamshire.

Her reputation as a pioneer in the thinking of the early history of the computer is unquestionably deserved. Some even claim Lovelace was the world's first computer programmer, though as Babbage biographer and computer science historian Doron Swade MBE points out, Babbage's programs predate Lovelace's by seven years.

Lovelace became fascinated by the algorithms that the Analytical Engine might calculate, and one of the great tragedies in the history of computing is that she was not involved in Babbage's work more. In August 1843, Ada wrote a long letter to Babbage suggesting that he let her help manage all the aspects of the Analytical Engine build project that required the influencing of important people. But he rejected her offer. It is not clear why; the best guess is that while he greatly approved of her work in publicising his engines, and the Analytical Engine in particular, he felt uncomfortable about letting Ada be involved in the project itself. What is fascinating is that even after Babbage's curt rejection of Ada's offer of help, she and Babbage remained lifelong friends.

While Babbage never completed a Difference Engine or an Analytical Engine himself, in 1991 a team at the London Science Museum – working under Swade's leadership – completed the fully working full-size calculation element of the Difference Engine. In 2002, they successfully completed a full-scale working Difference Engine. The project took 17 years to complete and is a most impressive sight: a magnificent piece of pioneering 19th-century engineering realised in the 20th century.

Today, Ada is quite rightly seen as an icon of feminist scientific achievement, a heroine of the mind, and one of the earliest visionaries in the early history of the computer. H

James Essinger is the author of *Ada's Algorithm*, a biography of Ada Lovelace, and of the forthcoming biography of Charles Babbage, *Machines of the Mind*. (James Essinger warmly acknowledges the kind assistance given him with this article by Doron Swade MBE)

BRUNEL A HARD TASKMASTER

Brunel (right) with engineers including John Scott Russell (far left) who worked on the design with him, at the launch of the ss *Great Eastern*, 1857

IK Brunel built the most ambitious bridges, ships and railways of the 19th century. He may have been one of our greatest Britons but, as **Steven Brindle** reveals, this engineering genius was far from being the easiest man to work for

Isambard Kingdom Brunel was one of the great creators of the 19th century. From his office at 18, Duke Street, London, he controlled an engineering empire: a professional staff that was in the order of 30 engineers, clerks and draughtsmen, usually working on several different railway lines, and other projects, at one time.

What was it like to be part of Brunel's team? Here is the testimony of John Brunton, then a humble assistant engineer working on a branch railway line in Dorset. On day in February 1855, he received an abrupt telegram from Duke Street ordering him, without explanation, to present himself there at 6am the following morning. Brunton packed a case, said goodbye to his wife, and left for town immediately.

At six the next morning: "a footman in livery opened the door, and told me in reply to my enquiry that Mr Brunel was in his office room expecting me. I was ushered into the room blazing with light, and saw Mr Brunel sitting writing at his desk. He never raised his eyes from the paper at my entrance. I knew his peculiarities, so walked up to his desk and said shortly 'Mr Brunel, I received your telegram and here I am'. 'Ah', was his reply, 'here's a letter to Mr Hawes at the War Office in Pall Mall, be there with it at ten o'clock.' He resumed his writing and without a further word I left his office."

The upshot, in fact, was that Brunton was sent out to Turkey, to supervise the construction of a prefabricated hospital for British troops, invalids from the Crimean war, which Brunel was then in the process of designing. The whole hospital, housing 1,100 beds, was designed, built, shipped and assembled in less than 10 months. Brunel must have realised that Brunton had great organisational abilities, which would be crucial to the success of this remarkable operation. But why this extraordinary treatment of an evidently capable and valued employee (Pall Mall was no more than a 15-minute walk from Brunel's office)? The answer is that Brunel, in all his working relationships, was a dictator. As we shall see, a need to be in complete control emerges time and time again, as a theme in his correspondence.

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His father Marc, above, gave Brunel a rigorous engineering education

ISAMBARD KINGDOM BRUNEL (1806-59)

Brunel was one of Britain's greatest 19th-century civil engineers. He spent 15 years on the GWR line from London to Bristol and his superb engineering and design skills can be seen in the bridges, stations, viaducts and tunnels that he built for it. From 1838, his pioneering steamships ss *Great Western*, ss *Great Britain* and ss *Great Eastern* changed the face of transoceanic navigation. His works of civil engineering, many of which are still in use, included dock improvements at Bristol and Sunderland, innovative iron bridges at Chepstow and Saltash, and the Hungerford Suspension Bridge across the Thames. His design for the Clifton Suspension Bridge was completed after his death, aged just 53.

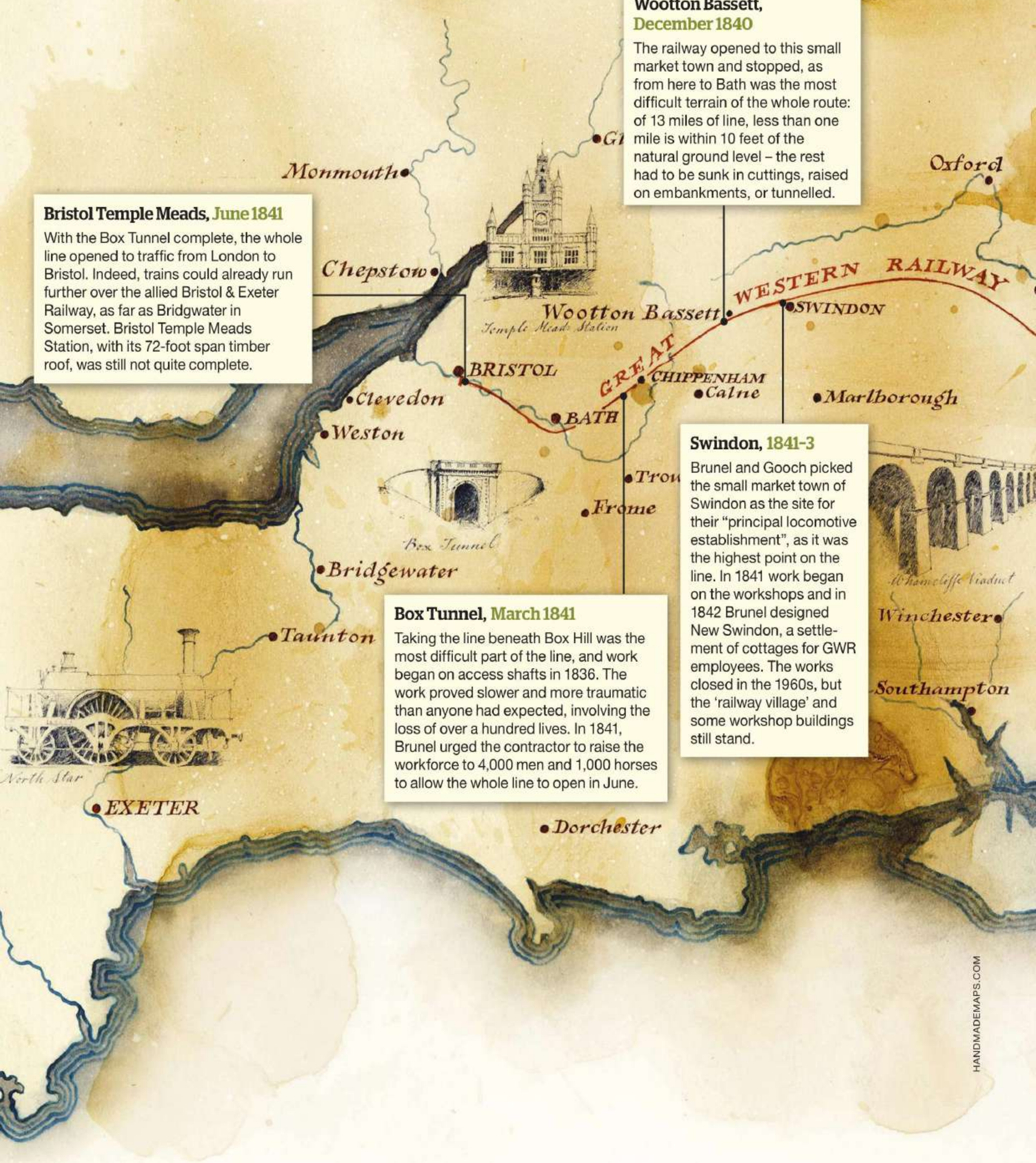
Tough schooling

Brunel had been trained in a hard school: it was a unique education, provided by his brilliant engineer father, Sir Marc Brunel. Sir Marc provided him with the best mathematical education available at the Lycée Henri IV in Paris, then with engineering apprenticeships in the best workshops of the day, those of Louis Breguet in Paris and Henry Maudslay in London. But Isambard was learning much more than just engineering: he was learning how precarious life could be, in the turbulent market economy of late-Georgian Britain. His father, the most brilliant inventor of the age, was alas no businessman: several of his ventures failed, and in 1821 both Marc and his wife Sophia were imprisoned for three months in the notorious Marshalsea for debt. Isambard, then 16, was at school in Paris.

Returning to England, Isambard became his father's apprentice. In 1827, aged 20, he became the resident engineer on Marc's Thames Tunnel, the most daring feat of civil engineering that had ever been attempted. A year and a half of backbreaking effort followed, but Isambard somehow had time to keep a remarkably revealing personal diary. This entry is from October 1827: "As to my character. My self-conceit and love of glory or rather approbation vie with each other which shall govern me... I often do the

Building the Great Western Railway

The 118-mile railway line from London to Bristol was the longest ever undertaken, and to conquer its difficult terrain required many bridges, viaducts and tunnels, as well as stations – and Brunel was personally responsible for most of the design work



Wootton Bassett, December 1840

The railway opened to this small market town and stopped, as from here to Bath was the most difficult terrain of the whole route: of 13 miles of line, less than one mile is within 10 feet of the natural ground level – the rest had to be sunk in cuttings, raised on embankments, or tunnelled.

Bristol Temple Meads, June 1841

With the Box Tunnel complete, the whole line opened to traffic from London to Bristol. Indeed, trains could already run further over the allied Bristol & Exeter Railway, as far as Bridgwater in Somerset. Bristol Temple Meads Station, with its 72-foot span timber roof, was still not quite complete.

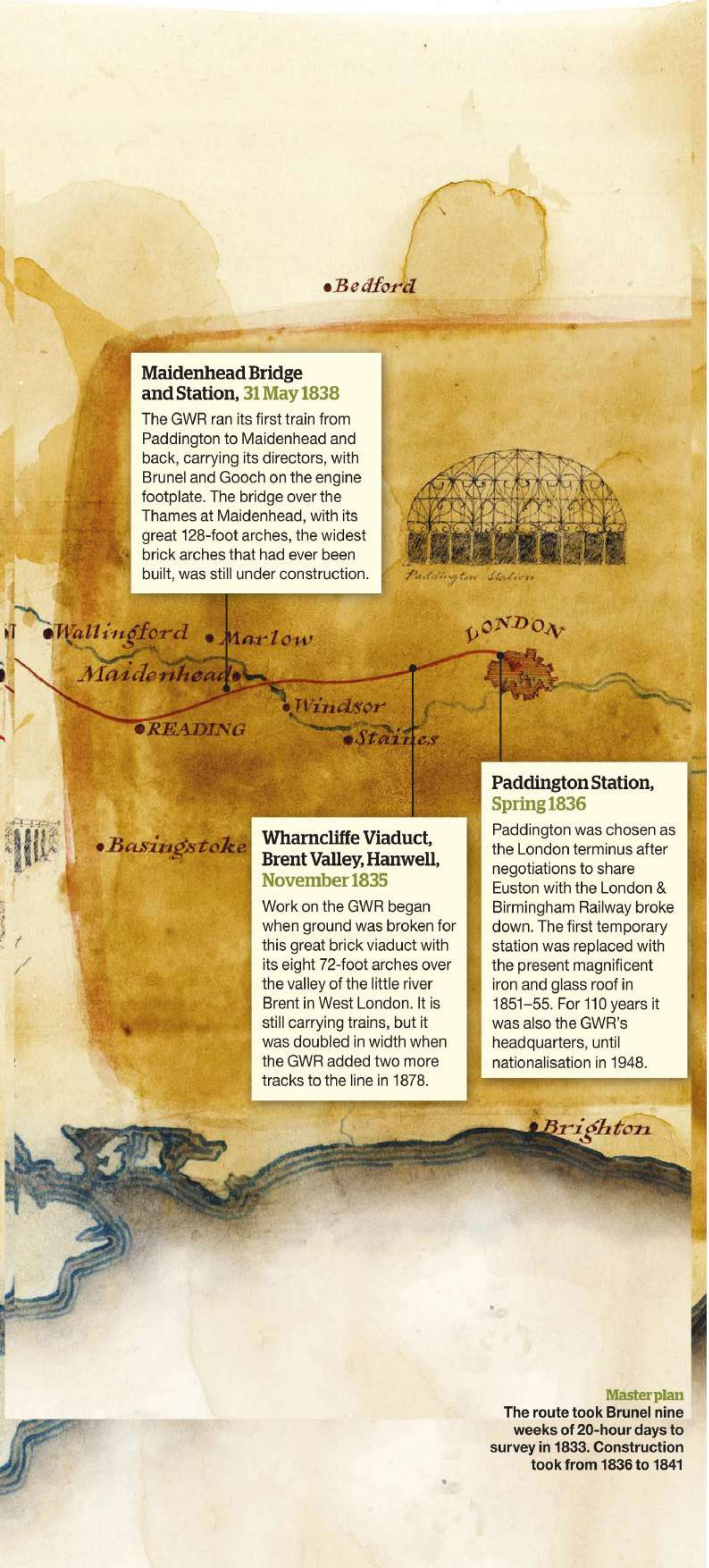
Swindon, 1841–3

Brunel and Gooch picked the small market town of Swindon as the site for their "principal locomotive establishment", as it was the highest point on the line. In 1841 work began on the workshops and in 1842 Brunel designed New Swindon, a settlement of cottages for GWR employees. The works closed in the 1960s, but the 'railway village' and some workshop buildings still stand.

Box Tunnel, March 1841

Taking the line beneath Box Hill was the most difficult part of the line, and work began on access shafts in 1836. The work proved slower and more traumatic than anyone had expected, involving the loss of over a hundred lives. In 1841, Brunel urged the contractor to raise the workforce to 4,000 men and 1,000 horses to allow the whole line to open in June.

HANDMADEMAPS.COM



Maidenhead Bridge and Station, 31 May 1838
The GWR ran its first train from Paddington to Maidenhead and back, carrying its directors, with Brunel and Gooch on the engine footplate. The bridge over the Thames at Maidenhead, with its great 128-foot arches, the widest brick arches that had ever been built, was still under construction.

Wharncliffe Viaduct, Brent Valley, Hanwell, November 1835
Work on the GWR began when ground was broken for this great brick viaduct with its eight 72-foot arches over the valley of the little river Brent in West London. It is still carrying trains, but it was doubled in width when the GWR added two more tracks to the line in 1878.

Paddington Station, Spring 1836
Paddington was chosen as the London terminus after negotiations to share Euston with the London & Birmingham Railway broke down. The first temporary station was replaced with the present magnificent iron and glass roof in 1851–55. For 110 years it was also the GWR's headquarters, until nationalisation in 1948.

Master plan
The route took Brunel nine weeks of 20-hour days to survey in 1833. Construction took from 1836 to 1841

Brunel wrote "It is an understood thing that all under me are **subject to immediate dismissal at my pleasure"**

most silly, useless things to appear to advantage before, or attract the attention of, those I shall never see again or who I care nothing about. My self-conceit renders me domineering, intolerant, nay, even quarrelsome, with those who do not flatter."

The Brunels' efforts were rewarded with calamity, when the tunnel flooded for the second time, in January 1828. Isambard was almost killed, the project went into abeyance, and at the age of 22 he was effectively unemployed (as was his father). Five years of intermittent employment on minor projects followed: five years in which the railway revolution was beginning. The Brunels, their efforts apparently wasted down the unfinished black hole of the tunnel, seemed doomed to remain on the sidelines.

Isambard's diaries vividly convey his frustration: "It's a gloomy perspective yet bad as it is I cannot bring myself to be downhearted… After all, let the worst happen – unemployed, untalked of – penny-less (that's damned awkward)… My poor father would hardly survive the [failure of the] tunnel. My mother would follow him – here my invention fails. A war now and I would go and get my throat cut and that would be foolish enough. I suppose a sort of middle path will be the most likely one – a mediocre success – an engineer sometimes employed and sometime not – £200/£300 a year and that uncertain."

It seems clear that these early struggles, and the memory of his father's difficulties, were fundamental in the formation of Brunel's remarkable, driven personality. The barren years ended in the greatest turning-point of his life, when in March 1833, approaching the age of 27, he was appointed engineer to the newly-formed Bristol Railway, soon renamed the Great Western Railway. He completed his survey for them in nine weeks and presented his plans. In July his appointment was confirmed, and the great work of designing the 118-mile line could begin. Up to now, he had never really employed staff at all. Now he had to set up an office and a team. Among the first to be

appointed was his chief clerk, Joseph Bennett, who remained with him for the rest of his life. Draughtsmen, clerks, engineers, all had to be taken on.

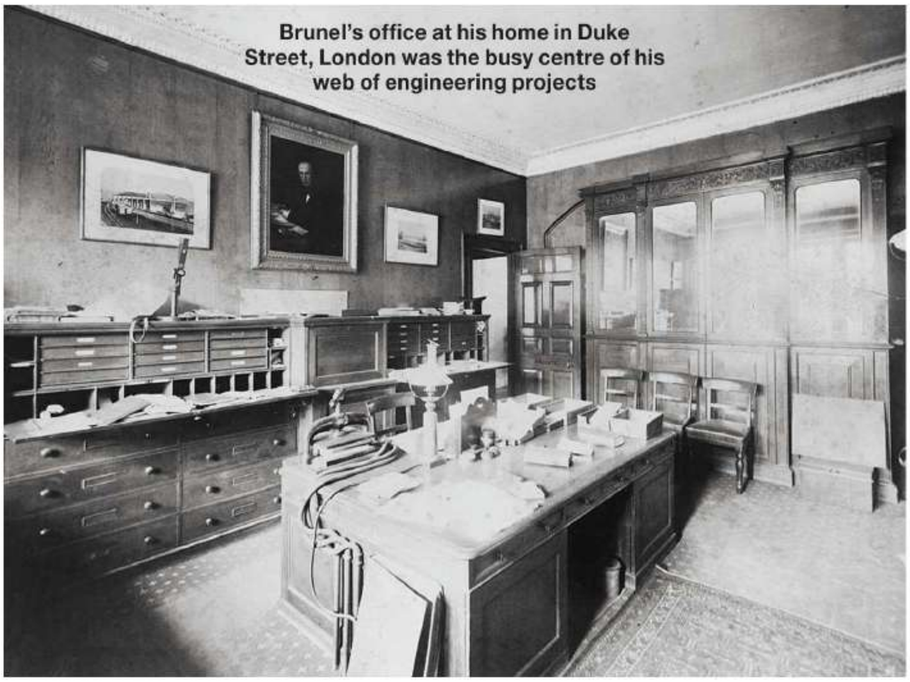
After 1833, Brunel was too busy ever to keep a regular personal diary again: instead we have the office diaries, covering much of the 1840s and 1850s. They reveal a barely believable timetable. During the planning of the GWR in 1834, Brunel had confided to his first senior assistant, John Hammond: "between ourselves it is harder work than I like. I am rarely much under 20 hours a day at it." The office diaries suggest that, even so, Brunel worked at least 16 hours a day, six days a week, for the rest of his life. From early in the morning until well into the evening, he was engaged in meetings, or visiting his works in progress, or appearing before parliamentary committees. Where, then, did he find time for the vast quantities of writing and design work, for which we have clear evidence in the shape of his immense personal archive?

Another assistant, GT Clark, left this account: "I never met his equal for sustained power of work. After a hard day spent in preparing and delivering evidence, and a hasty dinner, he would attend consultations till a late hour; and then, secure against interruption, sit down to his papers, and draw specifications, write letters or reports, or make calculations all through the night. If at all pressed for time he slept in his armchair for two or three hours, and at early dawn he was ready for the work of the day. When he travelled he usually started about four or five in the morning, so as to reach his ground by daylight… This power of work was no doubt aided by the abstemiousness of habits, and by his light and joyous temperament. One luxury, tobacco, he indulged in to excess, and probably to his injury."

In total control

Did Brunel really need to work so hard? The reason he did was that he was not at all good at delegating, or even at collaborating. His friend and rival, Robert Stephenson, the only one of his contemporaries whose achievements could really be said to match his, found it natural to collaborate with others over design issues, or delegate important pieces of work to members of his team: Brunel could not, or at any rate did not, do this.

The 50-odd volumes of his sketchbooks, now in Bristol University Library, prove beyond doubt that he was ultimately responsible for most of the real design work on his railways: his staff were there to take measurements, provide data, work his sketches up, and oversee the contractors as



Brunel's office at his home in Duke Street, London was the busy centre of his web of engineering projects

they turned the designs into reality.

His need for control, which emerges in his correspondence, was fundamental. Here he is, in 1851, on his conception of his own role: "I never connect myself with an engineering work except as the Directing Engineer who, under the Directors, has the sole responsibility and control of the engineering, and is therefore 'The Engineer'." And here he is, in June 1836, writing to William Glennie, on the latter's application for a post as assistant engineer with responsibility for the Box Tunnel: "what I offer now must not be a certain or permanent position. My responsibility is too great to allow of my retaining… anyone who may appear to me to be inefficient… it is an understood thing that all under me are subject to immediate dismissal at my pleasure. It is for you to decide if you are likely to proceed satisfactorily, and whether the chance is sufficient inducement".

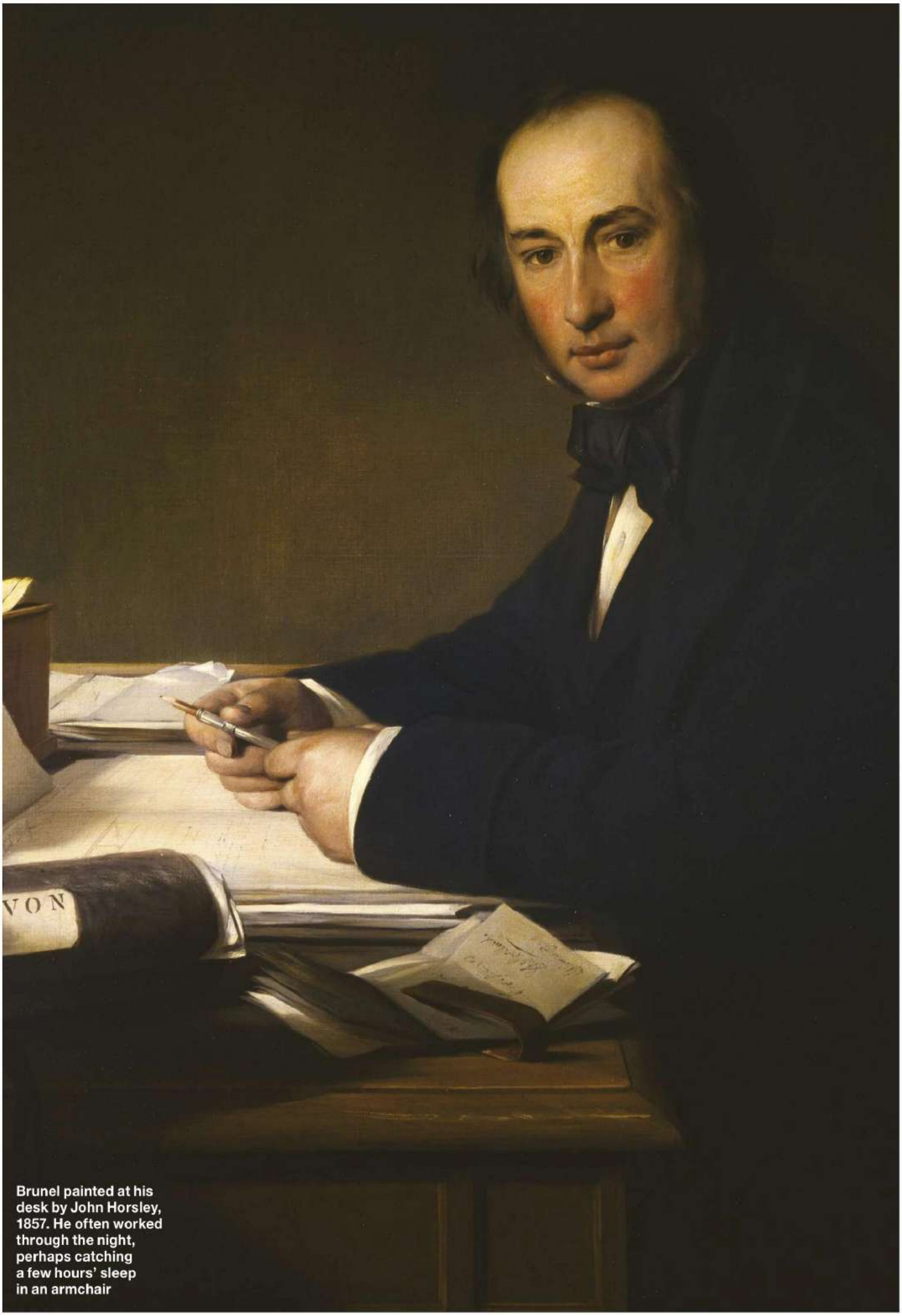
Brunel, evidently, was not a man to tolerate slackness in his employees, and where he detected it, he was merciless. In 1836, he wrote to a young engineer called Harrison, working on the Wharncliffe Viaduct at the London end of the line: "My Dear Sir, I am very sorry to be under the

Brunel became notorious for his insistence on **exceptionally high standards**

necessity of informing you that I do not consider you to discharge efficiently the duties of assistant engineer and consequently, as I informed you yesterday, your appointment is rescinded from this day. A great want of industry is that of which I principally complain, and thus it is entirely within your power to redeem the situation." Brunel offered Harrison a further period of employment "on trial", but on the same day, Harrison had forwarded the bill for a 'circumferentor' (a kind of theodolite), which Brunel had ordered him to buy. Harrison had misunderstood Brunel's instruction, thinking that he wanted the instrument to be bought for the company. Brunel re-opened the above letter, and added the following note: "You have acted with reference to this in a manner I do not choose to pass over. It indicates a temper of mind which excludes all hope of your profiting from the new trial I had proposed. You will please consider yourself dismissed from the Company's service on receipt of this letter."

Praise where it's due

Yet Brunel, for all his apparent harshness, was capable of appreciating loyal service. His trusted assistant, Robert Pearson Brereton, was sent in 1844 to be Brunel's man on the spot in designing the new Piedmont Railway. Italian officialdom proved impossible to work with, and Brunel wrote to the minister responsible: "My assistant, a peculiarly energetic, persevering young man, writes to me declining to remain as feeling entirely disheartened at the constant interference with every detail – and at the entire absence of confidence." Brunel was also perfectly capable of appreciating



Brunel painted at his desk by John Horsley, 1857. He often worked through the night, perhaps catching a few hours' sleep in an armchair

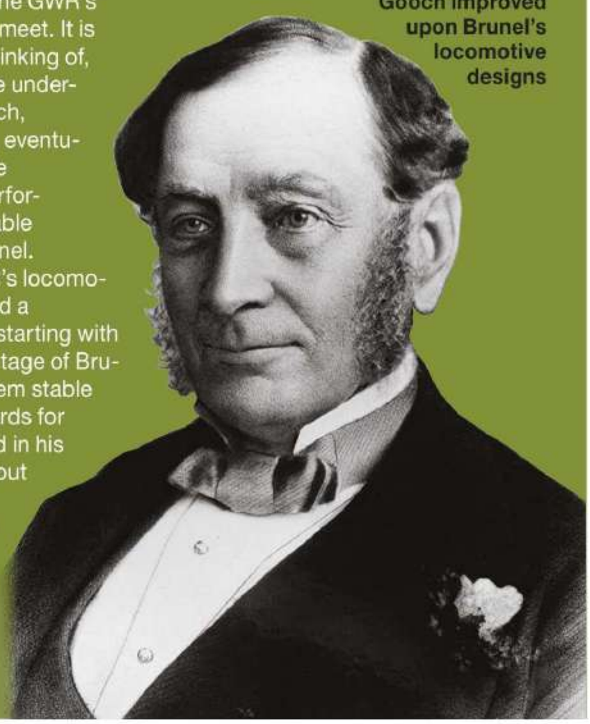
BRISTOL CITY MUSEUM AND ART GALLERY–BRIDGEMAN ART LIBRARY/JULIA ELTON

Tension and Teamwork: *Daniel Gooch and Brunel*

Overshadowed by the showier Brunel, Gooch was one of the period's great engineers, who played a pivotal role in fulfilling the more famous man's visions

Daniel Gooch (1816–89) started as an apprentice in Robert Stephenson's locomotive works, Newcastle, where his talent for engineering was developed. In 1837 Brunel selected the 20-year-old as the GWR's first locomotive superintendent. Apart from a brief period, he was to be associated with the company for the rest of his life. Brunel's initial ideas on locomotive design were unusual, and he set difficult standards for the GWR's locomotive manufacturers to meet. It is not at all clear what he was thinking of, but the resulting engines were underpowered and unreliable: Gooch, responsible for running them, eventually had to make it clear where responsibility for their bad performance lay, causing considerable tension between him and Brunel.

Allowed to design the GWR's locomotives himself, Gooch produced a superlative series of designs starting with the Firefly class, taking advantage of Brunel's broad gauge to make them stable as well as fast, setting standards for speed and safety not bettered in his lifetime. He planned and laid out the GWR's new locomotive works at Swindon, opened in 1843, and managed the production of most of the company's locomotives, rolling stock and rails. After disagreements with the GWR's board he was forced to resign in 1864. He was closely involved in the Anglo-American Telegraph Company, which laid the first Transatlantic cable using Brunel's *Great Eastern*. He returned to the GWR as Chairman in 1865 (piloting the company through a period when it was close to bankruptcy) and remained so until his death in 1889.



Gooch improved upon Brunel's locomotive designs

ability in his staff: "(Bell) has been known to me for about ten years – I have a high respect for his integrity and zeal in the service of his employers. He is a very well informed young man in his profession and particularly also in those branches requiring mathematical knowledge which are too often neglected. He has been engaged on docks works as well as railway construction and if I had an opportunity I should employ him myself."

But where an assistant called SC Fripp was concerned, for some reason Brunel was unable to sack the man, and instead, fired off the following missive: "Fripp. Plain gentlemanly language seems to have no effect on you. I must try stronger language and stronger methods. You are a cursed, lazy, inattentive, apathetic vagabond and if you continue to neglect my instructions I shall send you about your business. I have frequently told you, amongst other absurd, untidy habits, that of making drawings on the backs of others is inconvenient. By your cursed neglect of that you have wasted more of my time than your whole life is worth."

If Brunel was a tyrant to his staff, he was at least capable of being a benevolent one. Where the contractors who built his railways were concerned, Brunel treated them with, at best, haughty distance. Here he is writing to Messrs Grissell & Peto, one of the most reputable firms of the age, about the Wharncliffe Viaduct:

Brunel never gave his contractors any credit. **Instead, he treated them with unequalled severity**

"Gentlemen – just returned from Hanwell – observed that by far the largest proportion of the bricks upon the ground and actually in use were of a quality quite inadmissible… I examined the bricks on Monday last and gave particular orders to your foreman Lawrence respecting which I find he has neglected… I must request that he be immediately dismissed."

Brunel and his staff, having produced the detailed designs for a railway line, would divide it into sections to be let as contracts. Contracts were advertised for tender, and a master-set of drawings was made available at Duke Street: contractors were invited to take tracings. They visited the site, made their own calculations, and entered a tender, typically to build five or so miles of the line with cuttings, embankments and bridges. The successful contractor would be expected to put up a £5,000 bond as surety for completion.

Close to bankruptcy

Assembling the armies of men, and moving the vast quantities of earth, brick and stone needed to build a railway involved formidable logistical problems – especially then, in a rural landscape and a largely pre-industrial society. Yet Brunel never seems to have appreciated this, or given his contractors any credit for their organisational skills. Instead, he treated them with unequalled severity. He became notorious for his insistence on exceptionally high standards of workmanship, frequently rejecting materials, as seen above. He would refuse "coursed rubble" masonry of a quality which any other engineer would have accepted, and insist that it be replaced with finely-cut ashlar (blocks of squared and finished stone) instead. One consequence was that as the GWR proceeded, it became harder to find contractors to bid for his work.

Another consequence was that his contractors got into difficulties. James and Thomas Bedborough became insolvent during the construction of the Maidenhead Bridge and had to withdraw. Another

GETTY

Brunel's newly-built pedestrian Hungerford Suspension Bridge over the Thames, c1845

GETTY

contractor, William Ranger, had taken on the digging of the huge cutting near Sonning in Berkshire, and a series of tunnels between Bath and Bristol. The work was delayed by foul weather, as well as by Brunel's rejecting some of the work done, and in 1837 Ranger ran into difficulties. He, too, became insolvent, and Brunel was left with a problem. He solved it by transferring Ranger's contracts to the well-run firm of Hugh and David McIntosh, father and son. One might have thought that Brunel would have been grateful to them, but he treated them even more badly. Brunel would reject work on grounds of quality, or vary his design and expect them to cope without increasing their price.

Where there was a disagreement about price, by standard practice the arbitrator between the GWR and the McIntoshes was Brunel himself, and perhaps not surprisingly, he always found in favour of the former. If they were late with work, he withheld money. By 1840, Brunel was withholding from them payments to a total of over £100,000.

How could he get away with this? The answer would seem to be that the McIntoshes had sunk so much of their money in the building of the GWR that they didn't want to walk away from the job and risk a lawsuit: Brunel was effectively getting them to fund the building of the railway with their own credit. However, in 1840 old Hugh McIntosh died, and his son had had enough. The executors of the estate sued the GWR, and on Brunel's advice, instead of settling out of court, the company fought the case. Tactically, this may have seemed a shrewd move, as the Court of Chancery was notoriously slow and inefficient (as readers of Charles Dickens's novel *Bleak House* will know): at the time of Brunel's premature death in 1859 at the age of 53, the case was still grinding on.

However, unlike Dickens's Jarndyce family, the McIntoshes eventually received justice: on 20 June 1865, the lord chancellor ordered the GWR to pay them the £100,000, with 20 years' accrued interest and all legal costs. It came at a point when the GWR was severely financially embarrassed, and the following year the company came close to bankruptcy.

Brunel prided himself on his standards of conduct, and always insisted on gentlemanly manners from his staff. The McIntosh case, which seems difficult to reconcile with this view, was probably the most disreputable episode of his career. It is important to remember, in thinking about Brunel's extraordinary achievements, that for all his genius as a designer and his insistence on being in control, without his staff and his contractors he would have built nothing. There is a dark side to the Brunel legend, and it is important to bear this in mind if we are to come close to understanding this great – but difficult – man. H

Architectural historian **Steven Brindle** is the author of *Brunel: The Man Who Built the World* (Weidenfeld & Nicolson, 2005)

WAKING UP WITH

❶ Sleep like a log, on a stone

Since time immemorial, the morning routine has begun in bed. Sleep has always been a physiological necessity and the oldest evidence for a bed comes from the Middle Stone Age. Dating to 77,000 years ago, the remains of a hand-stitched mattress, woven out of leaves and rushes, have been found by archaeologists in South Africa. These cave dwellers presumably rolled out their mat on the floor, but if we jump to Neolithic Orkney (5,000 years ago), the inhabitants of Skara Brae slept on elevated beds carved from stone.

At the same time, in ancient Egypt, the nobility preferred beds that sloped downwards, or bowed in the middle. Oddly, while the poor slept on piles of cushions, the wealthy rested their heads on curved pillows carved from wood, ivory or alabaster. This was to protect their elaborate hair styles from morning bedhead.

❷ Whistle as you wake

We are certainly not the first to be startled from our slumber by a timekeeping gadget. Allegedly, the first alarm clock was invented by Greek philosopher Plato, who lived about 2,400 years ago. We don't know what this device looked like, but it may have been a water clock that used a draining mechanism to force air through a small gap, thereby producing a whistling sound to rouse Plato's snoozing students.

Mechanical clockwork was miniaturised in the 17th century, thanks to the discovery of the pendulum, allowing Charles II's subjects to own pocket watches. But it wasn't until the 20th century that alarm clocks began loitering on bedside tables. Indeed, factory workers in Victorian Britain were awoken by a knocker-upper who tapped on their windows with a long pole.

❸ Spend a penny on a potty

Our plastic toilet seat is not too dissimilar to the stone models used by the ancient Egyptians, though the flushing loo didn't arrive until Queen Elizabeth I's godson, Sir John Harrington, designed one in the 1590s. Yet he was too busy scribbling scandalous poetry to market his invention. So it wasn't until the arrival of Josiah George Jennings's washout toilets, unveiled at the Great Exhibition of 1851, before the middle class could abandon the potty in favour of plumbing.

We wouldn't dream of using the toilet today without wiping our bottoms, and it was no different for our Stone Age ancestors, who probably used moss and leaves on their backsides. Somewhat more unnervingly, Roman public toilets were equipped with a sponge, fixed on the end of a stick, which was used by successive lavatory visitors.

The Chinese were wiping with hygienic paper in the ninth century, but the west was a millennium off the pace. It took until 1857 for Joseph Gayetty to mass-produce modern toilet roll impregnated with aloe plant extract for hygienic lubrication.

❹ Exercise your right to take a shower

The modern shower was invented by William Feetham in 1767. Curiously, some versions were mounted on wheels, meaning the user had to be careful not to roll away on what was effectively a moistened skateboard. The following century also witnessed the bizarre arrival of the velodouche – a shower that only sprinkled water if you pedalled on an exercise bike.

But hygienic washing almost certainly extends back to the Stone Age. And, by the Bronze Age, the people of ancient Pakistan, the Harappans, were perfecting a public sanitation infrastructure that was arguably unrivalled until the 19th century. Though the Romans and Greeks built huge public bathhouses, heated by elaborate hypocaust systems, the Harappans delivered running water to most of their homes 2,500 years before ancient Athens was at its peak.

TOPFOTO/ALAMY/CORBIS/GETTY

THIS PAGE, LEFT TO RIGHT:
The remains of an elevated bed at the Neolithic site of Skara Brae in Orkney; a knocker-upper prepares to wake workers from their slumbers in 1936; latrines in Roman baths at Leptis Magna, Libya; this shower washed well-to-do Georgians in early 19th-century England

PLATO

From a Greek philosopher's alarm clock to bizarre Tudor toothbrushes, **Greg Jenner** explores the history of our morning routine

5 Put your pants on (if you're wearing any)

When Howard Carter discovered Tutankhamun's tomb in 1922, among the glorious golden treasures were also 145 pairs of underpants. The linen loincloth (shenti) was standard underwear of the time, regardless of class or wealth, but its origins seem even older. The mummified corpse of Ötzi the Iceman, who was murdered in the Tyrolean Alps 5,300 years ago, revealed he sported a goatskin loincloth.

Most European men and women went pantless until the mid-19th century, with ladies wearing long smocks under their dresses and men merely tucking their long shirts between their legs. However, the philosopher Jeremy Bentham (1748–1832) was surprisingly found to have been wearing boxer shorts when his preserved corpse was examined by modern conservators.

MARY EVANS/BRIDGEMAN/DREAMSTIME/WELLCOME IMAGES

6 Dress to impress the fashion police

Body lice thrive in the folds of clothing, and are thought to have branched off from their near relatives, head lice, thousands of years ago as a result of people adopting fabric clothing. We often depict Stone Age people in animal furs, but they also wove flax on primitive looms and used needle and thread to make clothes fit more snugly. In the Ice Age, well-insulated clothes were key to survival.

Today, fashion is more about looking good, but the 'fashion police' have been in operation for longer than you might think. In the Middle Ages there were laws proscribing certain colours and designs, and Edward IV demanded that purple, gold and silver fabrics be limited to royalty. You had to be of knightly class to get away with velvet.

In 17th-century Japan, a rule preventing merchants from wearing ornate robes led some to have the designs tattooed on their skin. This art of irezumi is still so highly regarded in Japan that people have been paid to bequeath their flayed skin to museums upon their death.

7 Spice on your cornflakes?

Strangely, our humble bowl of cornflakes first arrived in the 1890s as a treatment for patients with mental illness who masturbated too much. Dr John Harvey Kellogg believed that the lack of sugar and spice would reduce a person's sex drive. It was his brother, Will, who sprinkled the sugar back on top and made a fortune out of the Kellogg's brand.

Of course, every bowl of cereal needs a splash of milk, but this was only possible after the Neolithic farming revolution saw humans domesticate animals. Indeed, the mutated gene that allows most of us to drink cow's milk without suffering painful flatulence is only 6,000 years old, and the majority of the world's population don't have it.

THIS PAGE, LEFT TO RIGHT:
By the 20th century, most people were sporting underwear, as this image from the 1920 suggests; a man covered in the traditional Japanese irezumi tattoo in c1880; Dr John Harvey Kellogg chose not to use sugar in his cornflakes recipe in a bid to reduce patients' sex drive; an 1810 coloured engraving shows men who probably didn't own a toothbrush

8 Ask your slave to brush your teeth

People have been treating toothache for millennia, with evidence of dental drilling in Pakistan dating back 9,000 years. But avoiding surgery has always been preferable, so tooth brushing with a frayed twig was part of the morning routine for everyone from the medieval residents of India to the Elizabethans.

Roman aristocrats had slaves to brush their teeth for them, applying powdered antler horn to brighten the enamel. Oddly, the best available mouthwash at the time was human urine imported from Portugal.

The Chinese invented the modern toothbrush, but it never reached Europe, so the reinvention is credited to William Addis who, in 1780, inserted horsehair into a pig bone. But even Addis didn't recommend brushing twice a day – that advice came from US army hygiene experiments in the Second World War. H

Greg Jenner has been the historical consultant for every series of the BBC's multi-award-winning *Horrible Histories* series

DISCOVER MORE

BOOK

▶ **A Million Years in a Day: A Curious History of Everyday Life** by Greg Jenner (Weidenfeld & Nicolson, 2016)

TELFORD
The man who built modern Britain

From awe-inspiring aqueducts to fast, smooth roads, no building project was, it seems, beyond the genius of Thomas Telford. **Julian Glover** hails an engineer whose achievements arguably outshine those of Brunel

Industrial revolutionary genius

Engineer Thomas Telford (left), painted in the heyday of his career in 1822 by Samuel Lane. His designs included:

1 The Menai Bridge (also shown in box 5) wasn't the first suspension bridge, but is arguably the most impressive

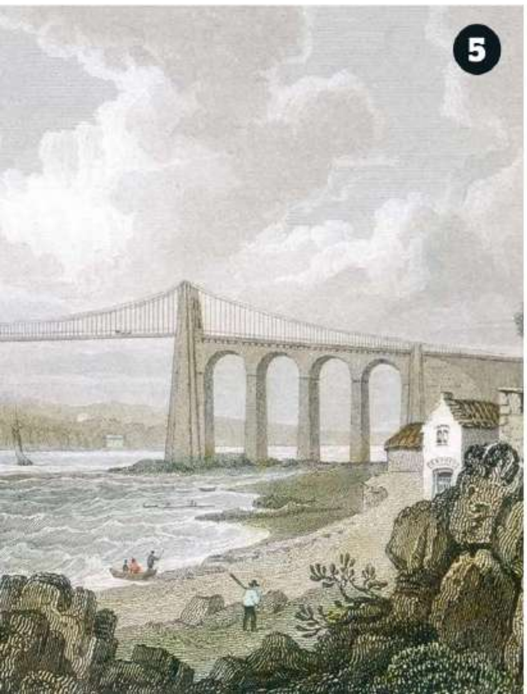
2 The Pontcysyllte Aqueduct, which still carries vessels high above the river Dee over two centuries after it was completed in 1805

3 St Katharine Docks, London, as depicted during official opening celebrations on 25 October 1828

4 The 60-mile Caledonian Canal, completed in 1822, which connects the east and west coasts of Scotland

5 The Menai Bridge in an 1830 illustration viewing it from Anglesey

6 Göta Canal in Sweden, opened in 1832 to provide a link between Gothenburg and the Baltic Sea



In 1829, two great engineers from two contrasting centuries clashed over the building of one famous bridge. The conflict pitted Thomas Telford (1757–1834) against Isambard Kingdom Brunel (1806–59) – the builder of magnificent canals and roads against the creator of the revolutionary Great Western Railway.

Though neither knew it at the time, this battle also marked the moment that Telford, celebrated in his lifetime as Britain's greatest civil engineer, but by that time old, unwell and out of his depth, began to be pushed aside in reputation by the 23-year-old Brunel.

Today the latter is a national hero, the embodiment of the can-do Victorian age, his best-known photographs showing him standing proud in his tall stovepipe hat. Telford, by contrast, is half-forgotten, his name attached to a 1960s new town in Shropshire but little else. His story deserves to be rediscovered – and the Clifton Suspension Bridge in Bristol is a good place to start.

Few of those who now cross this fine structure each day realise that it was here that Brunel took on Telford – and won. It is a spectacular sight, slicing above wooded slopes that tumble down to the water below, and is celebrated as a monument to Isambard Kingdom Brunel's brilliance. But the story of its creation is complex. Brunel depended on others when he drew up his plans. The bridge was not finished until after his death, to an altered design. And its engineer was almost Telford – not Brunel.

Building bridges

To understand all that happened, you need to rewind beyond the birth of either engineer. In 1754, Bristol wine merchant William Vick died, leaving £1,000 in his will with instructions that it be invested until the sum reached £10,000. He had believed that this amount would be enough to pay for a much-needed stone bridge from one side of the 75-metre-deep Avon Gorge to the other.

By 1829 Vick's legacy, now grown to £8,000, was still unspent. It was clear that a stone structure, if it could be built at all, would cost far more than that sum. So the city fathers decided to launch a competition inviting designs for a cheaper iron suspension bridge, using the latest technology of the day.

One man stood out as the obvious judge for the prize: Thomas Telford, the leading civil engineer in the land. Not long before, he had overseen the construction of the pioneering Menai suspension bridge, between mainland north Wales and the isle of Anglesey, which carried the new fast road (which he also engineered) from London to the port at Holyhead. When it opened in 1826 his edifice over the Menai strait was the most elaborate and impressive suspension bridge ever built – although not quite the first. It boosted Telford's fame even more.

Yet his bridge-building career ended in humiliation in Bristol shortly afterwards. Examining entries to the competition for the Avon Gorge bridge – among them designs drawn up by the young Brunel – Telford dismissed them all as inadequate, and was asked, instead, to submit his own entry.

This could have resulted in the finest Telford creation of all. But rather than the bold and light structure the city had hoped for, he proposed three timid, shorter spans, held up by mock Gothic towers built from the bottom of the gorge. It was the product of an engineering mind that had lost its spark after more than six decades of relentless work.

The design was ridiculed. Brunel, in particular, was openly scornful. "As the distance between the opposite rocks was considerably less than what had always been considered as within the limits to which suspension bridges might be carried," he wrote to the committee after his rejection, "the idea of going to the bottom of such a valley for the purposes of raising at great expense two intermediate supporters hardly occurred to me."

The younger man grabbed his chance. A second competition was run in which, initially, Brunel's design was placed second – but with help from his father, the outstanding engineer Marc Brunel, he persuaded the judges to award him first prize.

"Isambard is appointed engineer to the Clifton Bridge," Marc wrote triumphantly in his diary entry for 19 March 1830. "The most gratifying thing," he noted, was that the defeated engineers included "Mr T…d" – the only name in the whole of the diary that he could not bring himself to spell out in full, so strong were his feelings.

Victory was the making of Brunel, though not quite of the Clifton bridge; construction was halted in 1831 amid financial trouble, and it was not completed until 1864, after his death. The project rooted Brunel in the city of Bristol, which he soon connected to London with the Great Western Railway.

> Telford **deserves to be seen as Brunel's equal** – and, in some ways, as **more of a pioneer**

The debacle was, though, almost the end for Telford. Though he continued to work until his death just over four years later – after which he was buried in Westminster Abbey, the first engineer to be given that honour – his time in the front rank of engineers was over.

By then, Britain was changing. The Georgian age was giving way to the Victorian, just as horsepower was being pushed aside by steam and canals, and roads giving way to new railways. Brunel was the engineer of the future, Thomas Telford of the past.

Or so it seemed, for well over a century. Today, however, there is fresh recognition of Telford's importance to the industrial revolution and the creation of modern Britain. It is not to diminish Brunel's flair and success to say that Telford deserves to be seen as his equal – and, in some ways, as more of a pioneer. Unlike Brunel, for instance, who was drilled to learn engineering by his father almost from birth, Telford's youth offered no clear path to greatness.

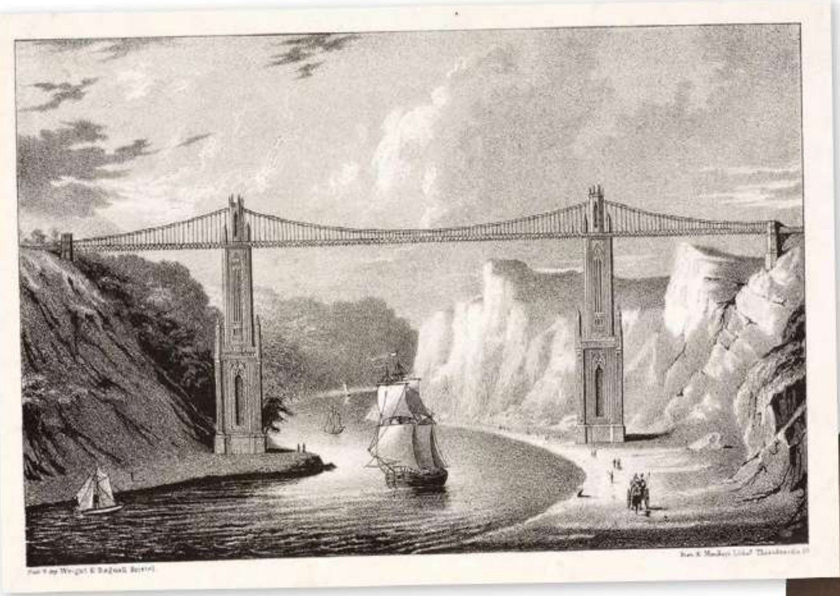
Evolution of an engineer

Thomas Telford was born in 1757 on a remote farm in the hills of the Scottish Borders, among a landscape little changed today, the gentle beauty of which illuminates any exploration of his life. Telford's father, a farm labourer, died before his son's first birthday, and the young Tammy Telfer – as he was known – was soon set to work guarding sheep on the fellsides.

He might have remained a poor farm worker all his life, but Telford was driven by a fiery internal energy. He forced himself to learn, to read books, and soon even to write poetry. In that he had something in common with Scotland's greatest poet, Rabbie Burns, who also started life in a farm in the Borders, and whom Telford came to venerate.

Most of all, however, Telford wanted to build. He trained as a stone mason; among his early tasks, it is said, was carving his father's gravestone, which can still be found in a quiet churchyard near his boyhood home; the inscription honours the older man as an "unblamable shepherd".

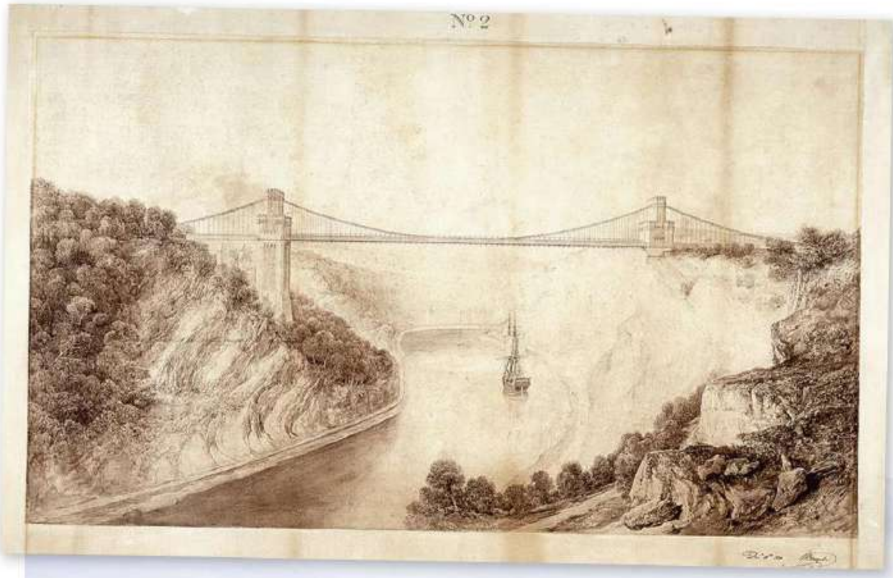
From that point Telford drove himself forward and up, always looking for opportunities and useful connections. First he went to Edinburgh, then to London, where he worked on the building of the grand new Somerset House by the Thames. By the 1780s he was in Shropshire, the county



Old master

LEFT: **Telford's 1829 design for a bridge across the Avon gorge in Bristol, with towers rising from the valley floor. This was ridiculed as old-fashioned by critics, including Brunel**

BELOW: **Telford depicted at the age of around 40 years, as his professional star was rising at the turn of the 19th century**



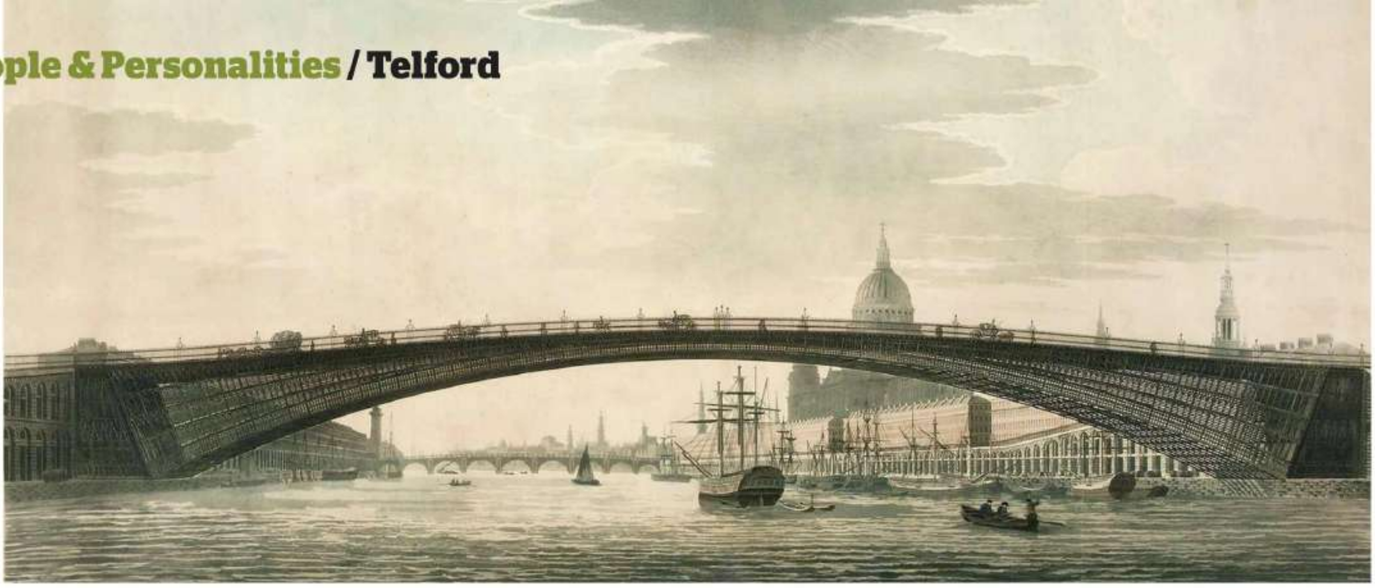
Young pretender

LEFT: **One iteration of Brunel's winning design for the bridge, dating from 1830**

BELOW: **Brunel's bridge today. Financial problems meant it was not completed until after his death**

INSET: **Robert Howlett's iconic 1857 photograph of Brunel in his trademark stovepipe hat**

GETTY



In 1799 Telford proposed to replace old London Bridge with a single iron arch spanning 180 metres (600 feet). The design was never used, and the bridge was eventually replaced by a structure of five stone arches designed by John Rennie

where he made his name and found his calling, first as an architect and then as a civil engineer.

It was an extraordinary time to be in Shropshire, in a region that is now very rural but which at that time was at the forefront of the industrial revolution. The great iron-works in Coalbrookdale were pioneering new techniques, and the world's first iron bridge had been built across the river Severn just before his arrival. It was here that Telford came to know the revolutionary possibilities of metal.

First, in 1797, he built – with help from others – a short, radical iron aqueduct on a new canal near what is now the town of Telford. But this was only a precursor to the great Pontcysyllte Aqueduct, opened in 1805, a ribbon of iron that still carries barges 38 metres above the river Dee on what is now known as the Llangollen Canal, just over the Welsh border from Shropshire. The Pontcysyllte is Telford's monument just as the Clifton Suspension Bridge is Brunel's. Both structures speak of individual genius and the ability to draw on the skills of others.

Some say that Telford should have shared the credit for his achievements more widely, though it was his skill in working with a team and managing many projects simultaneously that lifted him above the many other able engineers of the time. At Pontcysyllte, for instance, he was aided by a team including his nominal superior on the canal project, William Jessop. Men such as William Hazledine, the Shropshire ironmaster, went on to provide metalwork for most of Telford's greatest iron bridges, including the Menai.

Many of Telford's young pupils also went on to great careers of their own, among them Thomas Brassey, who built thousands of miles of railways all over the globe, making himself rich in the process. In 1820 Telford became the first president of the Institution of Civil Engineers, a body that shaped – and still shapes – the modern profession.

But Telford never became grand or formal, and shunned outward signs of wealth and status. Money never seemed to interest him much. Thick set, with dark hair, a rugged face and a Scottish accent, he was a man born to hard work outdoors who prided himself on his practical skills. He was also a flexible political operator with a deep, self-taught understanding of theory: his pocket notebooks are full of demanding mathematical calculations and architectural study. He read and wrote late into the night.

Telford worked hard and almost non-stop. There was no time and seemingly no desire for a marriage, family or partner. He had no siblings and, after the death of his mother, no immediate relations, but he had a number of close lifelong friends. In the right company he was cheerful, telling stories and making jokes with a sparkle in his eye that made people like him as soon as they met.

On the road

Telford was almost always on the move, keeping up a regular progress of inspection of his projects that, by the early years of the 19th century, reached into remote corners of England, Wales and Scotland. Roaming the country without a break, year in, year out, he must have travelled farther in Britain than any person alive – and even, perhaps, more than anyone ever had before. In the Highlands, for instance, supported by government commissions, he oversaw the construction of almost 1,000 miles of roads and countless bridges, including elegant, light iron structures, one of which still survives, leaping across the river Spey at Craigellachie.

> In the Highlands, he oversaw construction of almost 1,000 miles of roads and countless bridges **including elegant, light, iron structures**

Telford managed the construction of the wide Caledonian Canal, running from sea to sea across the Great Glen between Inverness and Fort William. This relentless, difficult, muddy task took two decades and could have been the focus of a lifetime's work. But Telford combined it with an extraordinary range of other schemes: rebuilding ports, erecting churches, designing water works, building bridges and constructing the fastest, best roads since the Roman era.

Telford's famous express route from London to Holyhead smoothed the journey to Dublin – a route that grew in importance once the new United Kingdom was established in 1801. He upgraded the existing road from the capital to Birmingham and on to Shrewsbury, and engineered an elegant new section on through the hills of Snowdonia, including the fine suspension bridge at Menai and another by Conwy Castle – the only one to retain its original chains.

And still there was more: a canal across Sweden, advice to projects in India, Russia and Canada, the new St Katharine Docks in London. All of it was impressive, but much of it was made redundant by technological change: the coming of steam and railways. Even as he died, in 1834, Telford was going out of date – and he knew it.

His creations are his memorial, built so well that the vast majority are still in use. You can drive on Telford's roads, walk across his bridges and ride boats along his canals. They are worth searching out – and with them the story of a life that helped build modern Britain. **H**

Julian Glover is a journalist and the author of *Man of Iron: Thomas Telford and the Building of Britain* (Bloomsbury, 2017)

GETTY

Science Stories

MINING

1815

Humphry Davy invents a life-saving lamp

Davy's safety lamp was designed to cool the gases within, making it less likely to overheat

Humphry Davy's (1778–1829) most famous fan was Mary Shelley, who studied his Royal Institution lectures on electricity and chemistry while she was writing Frankenstein. Davy's flamboyant presentations attracted so many elegant spectators that the street was made one-way – London's first – in order to cope with the traffic jams of horse-drawn carriages.

His flair for self-promotion had enabled Davy to climb rapidly through the social strata and move far away from his origins as the son of a Cornish woodcarver. This one-time apothecary was made a baronet to mark his invention of a safety lamp for coal miners – and in 1820, he attained the most prestigious position in British science by being elected president of the Royal Society.

Like Victor Frankenstein, Davy epitomised troubled genius. As a teenager, he taught himself the revolutionary ideas about oxygen and acids that were being developed in France, and he resolved to become the Isaac Newton of chemistry. A prolific poet and fanatical angler, Davy consciously aligned himself with the Romantic writers and artists of his generation. In the early 19th century, there was no consensus on how a man of science should behave. Should he (definitely not she!) be a methodical experimenter who systematically accumulates observations and tests theories? Or should he aim for flashes of instantaneous inspiration when watching an apple fall from a tree?

Through his dramatic experimental demonstrations and his powerful stage presence, Davy established himself as an authoritative expert who could manipulate the forces of nature to pry out its innermost secrets. In particular, he used current electricity – only recently made available – for exploring chemical substances. First he decomposed water, showing that it comprises only two elements: oxygen and hydrogen. After applying the same technique to alkaline solutions, Davy discovered two new inflammable metals: sodium and potassium. Patriotic Englishmen acclaimed Davy as a national hero who had redirected the course of chemistry.

Even so, Davy's critics never let him forget that during a two-year stint at the Pneumatic Institution in Bristol, his research into nitrous oxide had concentrated not on the gas's anaesthetic properties, but on its potential as a recreational drug inducing mind-enhancing experiences. But after he came to London in 1801, Davy turned towards more practical applications by attempting to improve British industry and agriculture. For his first major projects, Davy examined leather tanning and fertilisers, providing scientific justification for techniques that had been built up over centuries. In contrast, for his investigations of mining, Davy started with an existing problem and solved it by developing a new device inside his London laboratory.

> In 1820, he attained the most prestigious position in science – **president of the Royal Society**

From his Cornish childhood, Davy knew that pockets of gas could easily ignite underground, causing many fatal accidents. Through chemical experiments, he identified the composition of the 'firedamp' found in mines, and discovered that it would only explode at high temperatures. For his safety gas lamp, Davy introduced two important ways of preventing this dangerous overheating: he cooled the gases by passing them through narrow tubes, and he surrounded the flame with a protective sheath of metal gauze. Davy won huge acclaim for this invention, which saved many lives. On the other hand, by enabling miners to penetrate deeper and more dangerous seams, his lamp helped to increase their employers' profits. As so often happens, technological progress did not necessarily represent social improvement.

Words: Patricia Fara

BRIDGEMAN

HISTORY**EXPLORER**

The Scottish Enlightenment

The 18th century saw an extraordinary intellectual boom time in Scotland. Alexander Broadie explains how **Glasgow University** inspired some of the period's most brilliant thinkers

Professor Alexander Broadie on the balcony of Glasgow's Hunterian Museum. Broadie held the same university position as Scotland's "giant of moral philosophy", Adam Smith

Photography by Jeremy Sutton-Hibbert

Glasgow University's main building, a magnificent neo-Gothic edifice on top of a hill overlooking the city, dates from the middle of the 19th century. But parts of the building – in particular sections of its fine gateway, now known as Pearce Lodge, and the Lion and Unicorn stairway, next to the Memorial Chapel – can be traced back to the 17th century; the statues of the lion and unicorn (shown on page 108) that flank the stairway were created in 1690.

Both the stairway and the lodge form a visual link with the university's glorious past. During the Age of Enlightenment in the 18th century, Glasgow's was, in the fullest sense, an Enlightenment university, as indeed it still is.

The Enlightenment movement championed reason over tradition and was characterised by great scientific and intellectual achievements. It was a truly international phenomenon, yet shone nowhere more brightly than in Scotland, and in Scotland nowhere more brightly than in Glasgow University.

For a country to have an Enlightenment, two elements must be in place. The first is a large number of creative people who think for themselves instead of merely assenting to authority. The second is a level of toleration that permits such people to express themselves without risk of retribution.

On these two counts, by the standards of the day, Scotland was one of the most enlightened countries in 18th-century Europe. In many places, but especially in the cities of Aberdeen, Glasgow and Edinburgh, and particularly in their universities, there were creative thinkers, some of them geniuses, informing or even transforming the various academic disciplines.

In Aberdeen in the early days of the Enlightenment were men such as Colin Maclaurin, a brilliant mathematician who won warm praise from Sir Isaac Newton, and the liberal educational theorist George Turnbull. One of Turnbull's students at the city's Marischal College was Thomas Reid, who would later replace Adam Smith as professor of moral philosophy at Glasgow. He was the most important figure in the Scottish school of common sense philosophy, which was dominant in North America and France during the following century.

Meantime, at Edinburgh University we find the philosopher Dugald Stewart, the sociologist Adam Ferguson and the historian William Robertson. And living in the capital city, but not having university posts, were David Hume, one of the greatest philosophers of the Scottish Enlightenment, and James Hutton, whose *Theory of the Earth* has earned him the title 'founder of modern geology'.

At Glasgow University, along with Smith and Reid, was the philosopher Francis Hutcheson, the physician William Cullen, the chemist Joseph Black and the engineer James Watt.

These formidable thinkers took advantage of the Scottish religious and political authorities' relatively relaxed attitude to new and challenging ideas to set the agenda for cutting-edge research across Europe. Things were very different in France, whose many enlightened figures had to contend with an absolutist monarchy and church

JEREMY SUTTON-HIBBERT

"The Enlightenment shone nowhere more brightly than at Glasgow University"

PROFESSOR ALEXANDER BROADIE

Alexander Broadie pictured on Glasgow University's famous Lion and Unicorn staircase

Adam Smith, 'the father of economics'

and a powerful system of state censorship. One lumière was Denis Diderot, a writer hostile to Christianity, whose book, *Letter on the Blind* (1749), landed him in prison in the fortress of Vincennes for three months.

By contrast, though David Hume was widely (if wrongly) believed to be an atheist, he was never threatened with imprisonment. In fact, he was the life and soul of the societies to which he belonged, whose membership included ministers, judges, professors, aristocrats and artists, such as the painters Allan Ramsay and Henry Raeburn, and architects William Adam and his sons John and Robert.

No one illustrates the role of Glasgow in Scotland's Enlightenment better than that giant of moral philosophy, Adam Smith – a c1867 statue of whom stands near Bute Hall in the university's main building. Smith had a long relationship with Glasgow University: as an undergraduate, then a professor – first of logic and rhetoric and later of moral philosophy – and, for two years at the end of his life, as lord rector.

Smith is now widely hailed as the 'father of economics', and it was while lecturing at Glasgow University that he formulated the theories that would lead to his writing *The Wealth of Nations* (1776), a work long recognised as one of the greatest contributions to economic theory ever.

Smith famously argued the case for free trade, contending that trade barriers do not benefit the country that imposes them; on the contrary, he showed that protectionism causes a rise in prices and a lowering of employment prospects. He also argued that schooling should be made universally available and paid for by the government, even sketching out the syllabus that the schools should follow.

The natural sciences are no less a feature of the Scottish Enlightenment than are philosophy and political economy. During a period of 10 years at Glasgow, one of its professors (and a former student of Glasgow), the aforementioned Joseph Black conducted research into heat. In the course of this research, he probed the science behind two major natural phenomena, which he termed latent heat and specific heat. This work makes him one of the founders of the science of thermodynamics.

Among Black's closest collaborators was James Watt, scientific instrument-maker to Glasgow University. Watt produced a brilliant solution to the problem of how to construct an efficient steam engine – and, in doing so, helped transform the productivity of Britain's manufacturing industries.

Some of the scientific instruments used by men such as James Watt, Joseph Lister and Lord Kelvin are held at the university's magnificent Hunterian Museum, founded by Dr William Hunter (1718–83), a groundbreaking obstetrician and teacher. The museum, showcasing Hunter's remarkable collections of specimens, manuscripts and other Enlightenment material, opened to the public in 1807 and is hailed as one of the finest university collections in the world. H

"IT WAS WHILE LECTURING AT GLASGOW THAT ADAM SMITH FORMULATED THE THEORIES THAT WOULD LEAD TO *THE WEALTH OF NATIONS*"

Specimens from the Enlightenment period are on display at the university's magnificent Hunterian Museum

Alexander Broadie is an honorary professorial research fellow at Glasgow University. His books include *The Scottish Enlightenment* (Birlinn, 2007)

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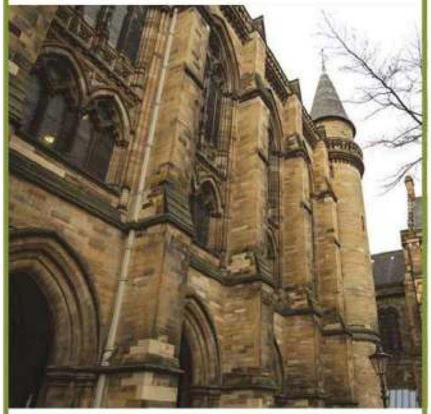
JEREMY SUTTON-HIBBERT

THE SCOTTISH ENLIGHTENMENT: **FIVE MORE PLACES TO EXPLORE**

VISIT

Glasgow University



The University of Glasgow
Glasgow G12 8QQ
● *gla.ac.uk*

1 Arniston House, Gorebridge, Midlothian

● *arniston-house.co.uk*

In 1726 Robert Dundas, Lord Arniston, commissioned the Enlightenment architect William Adam (1689–1748) to build a new country house on the site of the existing tower house. Completed by William's son John, this truly magnificent Palladian building, incorporating two rooms of the original tower house and with amazing baroque plaster-work by Joseph Enzer in the hall, remains largely unchanged. There have been Dundases at Arniston since 1571.

Arniston House is a Palladian gem that has barely changed in 250 years

ALAMY/THE ARNISTON ESTATE

2 Siccar Point, near Cockburnspath

● *scottishgeology.com*

Siccar Point, on the North Sea coast, 40 miles east of Edinburgh, is famous for displaying vertical strata of rock jutting up through horizontal strata of less resistant rock. The rocks' remarkable formation helped James Hutton (1726–97), a genius of the Scottish Enlightenment, formulate the idea of 'deep time' – the concept that the Earth is far, far older than the few thousand years suggested by creationists.

3 Robert Burns Birthplace Museum, Alloway, Ayr

● *burnsmuseum.org.uk*

The cottage in which poet Robert Burns (1759–96) was born was built in the 1730s; the south end, consisting of a living room and byre (cowshed), was built by his father, William, in 1757. It is now a fine museum. Nearby are the ruins of the Auld Kirk of Alloway, the scene of the demon revelry in Burns's 1790 poem *Tam o' Shanter.*

4 Edinburgh New Town

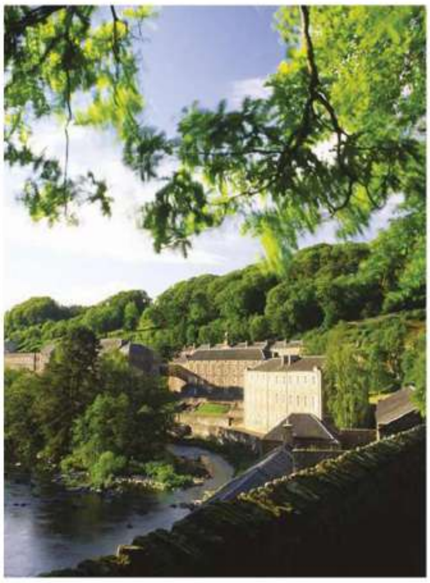
● *edinburgh.org*

Edinburgh New Town was begun in 1767 to a design by James Craig (1739–95) on land north of Edinburgh's densely populated Old Town. A classic gridiron plan, it consists of three principal east-west streets joining St Andrew's Square in the east and Robert Adams's Charlotte Square to the west. It was later expanded to the east and the north, forming a magnificent area of continuous Georgian layout and architecture. The nomenclature of the streets is Hanoverian and unionist, a reminder that an early design for Edinburgh New Town was in the form of the Union Jack. The Old and New Towns are now officially a World Heritage Site.

5 New Lanark, South Lanarkshire

● *newlanark.org*

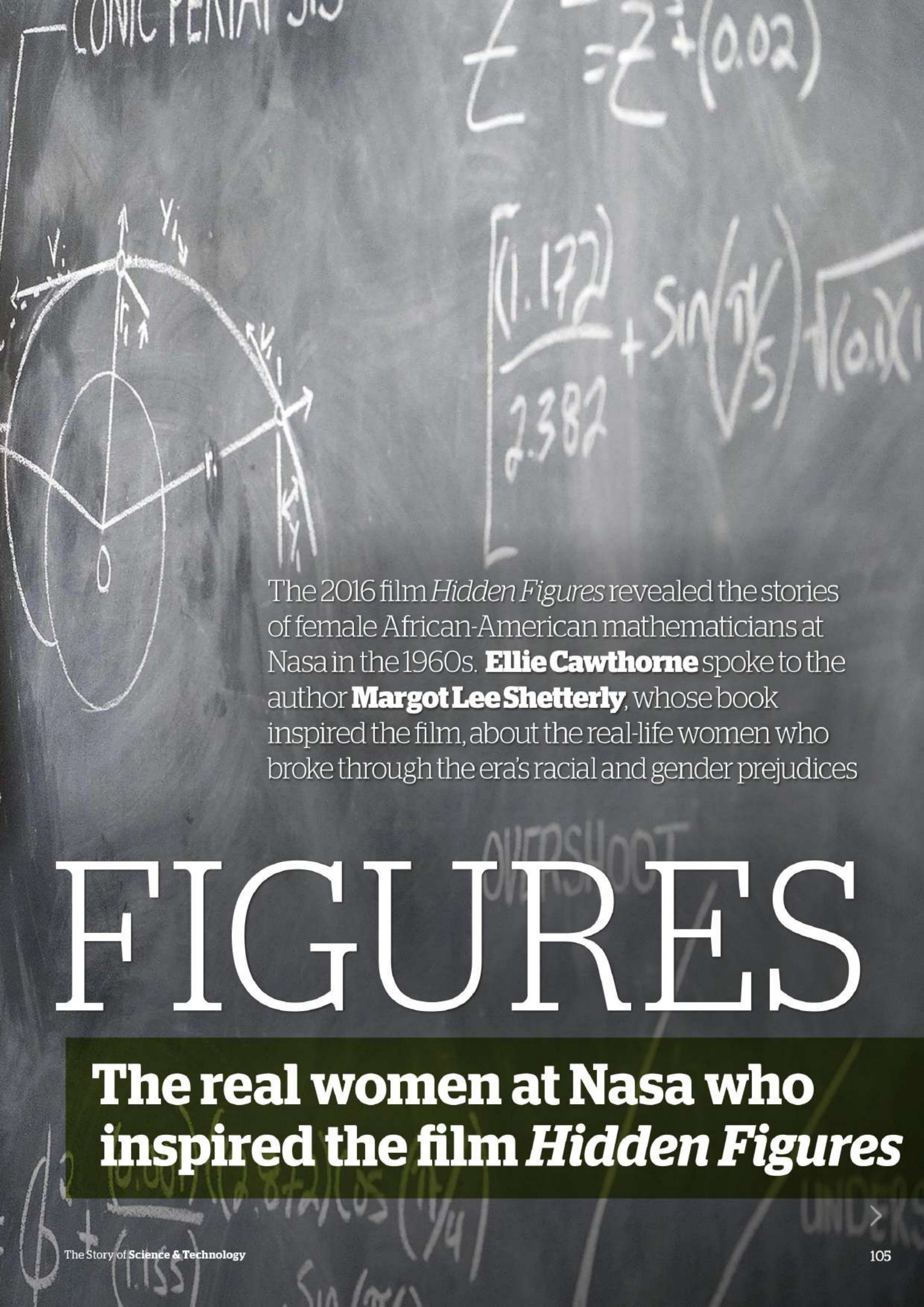
Now a World Heritage Site, this purpose-built mill village was founded by businessman and merchant David Dale (1739–1806) in 1785. The welfare and education of the workers, many of them children, was important to Dale. After 1799, his son-in-law Robert Owen introduced better safety rules, a contributory fund for medical care, and an astonishingly enlightened system of education for all. This was a realisation of Adam Smith's doctrine that economic activity should be within a moral framework.



New Lanark offered mill workers a very different way of life to their 19th-century counterparts

Mathematician Katherine Johnson was played by actor Taraji Henson (left) in the acclaimed film *Hidden Figures*, inspired by the story of the women who provided Nasa with important data needed to launch the programme's first successful space missions

HIDDEN

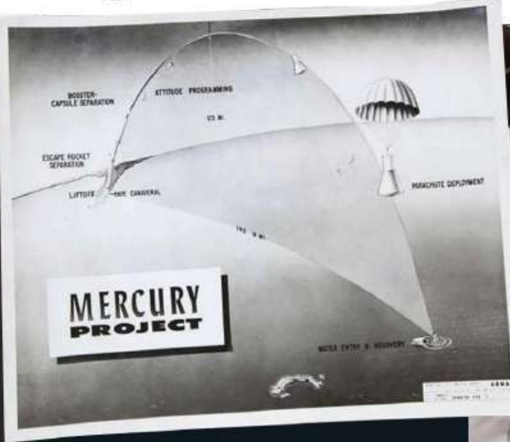


The 2016 film *Hidden Figures* revealed the stories of female African-American mathematicians at Nasa in the 1960s. **Ellie Cawthorne** spoke to the author **Margot Lee Shetterly**, whose book inspired the film, about the real-life women who broke through the era's racial and gender prejudices

FIGURES

The real women at Nasa who inspired the film *Hidden Figures*

The brilliant mathematician Katherine Johnson, shown here at work at Nasa in 1966



The trajectory of the first American in space in 1961 (above), was calculated by Katherine Johnson. Alan Shepard (right) was the man on that historic flight, part of Nasa's Mercury project to put a man into orbit around the Earth

How did you first come across this remarkable true story?

My dad worked at Nasa as an atmospheric scientist. So I spent my whole childhood going over to Nasa; Christmas parties with Nasa-themed Santas just seemed normal to me. The wonderful thing was that the very first scientist I knew, my dad, was black. For me, that's what science was. Many of the other scientists around me were also black, or women, or both. So I had a truly privileged position which normalised what women and African-Americans could do.

A few years ago my husband and I visited my parents, who were talking about some of the African-American women who worked at Nasa during the early years of the space race. I knew these women from the local community – they were my parents' friends. But my husband was so surprised; he couldn't believe he'd never heard this story.

While I knew these women, I didn't really know their stories – why they were at Nasa, what they were doing and why there were so many women who worked there. Investigating these stories set off a whole chain of dominoes, which eventually became *Hidden Figures*.

Why haven't we heard this remarkable story before?

There are a lot of reasons. One is that very much like the British ladies at Bletchley Park (the central site for British codebreakers during the Second World War), the work these women were doing was classified. During the space race and the Cold War there was a very real fear of espionage; people were looking for Soviets round every corner. But I think the bigger reason is that these women were unseen. They were in a segregated office and their work was considered 'women's work', meaning it was valued less. At this time, even if a woman was doing exactly the same thing as the engineers, who were predominantly men, she could be paid less and be given a lower job title. Now, with the distance of many decades and a different awareness, we are re-evaluating these women and their work. Our eyes are now sharp enough to see them the way they need to be seen.

> "These women were unseen. They were in a segregated office and their work was considered 'women's work', meaning it was valued less"

These women weren't just doing something that no African-American women had done before, but something that no-one of any race or gender had done before. They were on the pioneering edge of science and technology, which was thrilling for them. And they were doing all of this without calculators. They were called 'computers' – this was a time when a 'computer' was a job title rather than an object on your desk. It's amazing what these women were able to do with just data sheets. There's more computing power in a toaster than what they had to send people into space.

While these were exceptional women – I want to make that clear – they weren't the exception. The thing that was thrilling to me was that this wasn't the story of a first, or an only, or even just a few. At this time, women mathematicians were the rule, not the exception. From 1935 to 1980, counting women of all backgrounds and races, there were more than 1,000 women doing this work for Nasa. That's a huge amount. We have this idea that women aren't good at maths and don't exist in these fields, but that simply isn't the case – *Hidden Figures* is correcting that misconception.

What was it like to be an African-American woman during the 1960s? What kind of obstacles did these women face in everyday life?

Segregation was still in place, and it was very important for me in the book to show the real banality of that, the daily humiliations and slights. These women were creating calculations to make something happen that had never happened in the history of humanity, and yet they still had to go to the 'colored bathroom'. That is how these women experienced segregation in their everyday lives – they may not have been barked down by dogs in the street, but they faced humiliation at every turn.

Most black women at the time were working as domestic servants, or in factories, really scraping just to get onto the first rung of the social ladder. The African-American

GETTY

Mary Jackson began her career in 1951, an era in which female engineers were rare. She continued to work at Nasa until retirement in 1985

Dorothy Vaughan and Leslie Hunter (seen in 1950), two of the female mathematicians hired as 'human computers' on the space programme

Hidden Figures (above) dramatises the Nasa careers of (l-r) Dorothy Vaughan (actor Octavia Spencer), Katherine Johnson (Taraji Henson) and Mary Jackson (Janelle Monáe)

women working at Nasa were largely middle class and educated, so even within the black community these college-educated women were outliers. They were generally expected to go into teaching, which was a prestigious job at the time, but it didn't pay very well. Working as professional mathematicians, they could make two or three times more than as teachers.

Considering the social situation in the United States at the time, how did these women manage to get jobs at Nasa?

During the Second World War, the demand for aircraft exploded, while at the same time, a lot of male mathematicians and engineers went off to fight. There was a real need for people who could do the maths, so Uncle Sam put out the call.

At the same time, the civil rights leader A Philip Randolph (1889–1979) was pressuring the federal government to open up war jobs to African-Americans, Mexicans, Poles and Jews – a lot of people who were being discriminated against during this period. Once that door had been opened, these women just walked through, and after the Second World War ended they basically resolved: "I'll be damned if I'm leaving this job."

This was a fascinating period in US history – coming out of the Second World War, there was a certain idealism that pervaded the space race, the advance of technology, the civil rights and women's rights movement – a belief in a better America. Even as there was lot of conflict, there was also a lot of optimism.

GETTY

What was the workplace at Nasa like for these African-American women?

As well as an aeronautical laboratory, Nasa really was a weird social laboratory at this time. On the one hand, they had a segregated office with a 'colored bathroom' and a 'colored cafeteria'. But on the other hand, Nasa was more progressive than many other aircraft or commercial agencies at the time. They employed more women and African-Americans and these employees had access to some very high-level work.

Many of the engineers at Nasa came from the north or west of the US [where racial divisions were less pronounced] or abroad – from Germany, Britain and Italy. This meant that many of the employees weren't used to living under Jim Crow segregation [the repressive laws and customs used to restrict black rights in the southern states from 1877 to the mid-1960s] and actively opposed it. So Nasa was definitely a weird in-between zone, a very unusual place.

You interviewed many of these women, including Katherine Johnson. What were they like?

They loved talking about the details of their work, and had a real passion for Nasa, despite all the difficulties. The women I spoke to really loved their jobs and the people they worked with – Katherine Johnson talked about her colleagues being like brothers and sisters.

They are also hugely humble and modest. When they first heard that their story was going to be told, through my book and the film, their reactions were: "what's the big deal, what's the hoopla, why is everyone interested?" But although they loved the work, they did know that they didn't get the accolades they deserved. They recognise the power of their stories to inspire younger women and feel proud about that.

Can we see the legacy of these women and their achievements today?

Absolutely. All you have to do is look at Nasa's astronaut corps, which is very diverse. The head of Nasa is a black man, and the second in command is a woman. Women hold a lot of leading roles at Nasa. We're still having discussions about how to get more women and African-Americans into STEM fields [science, technology, engineering and mathematics], so we need to be aware of these stories – there's a lot they can teach us.

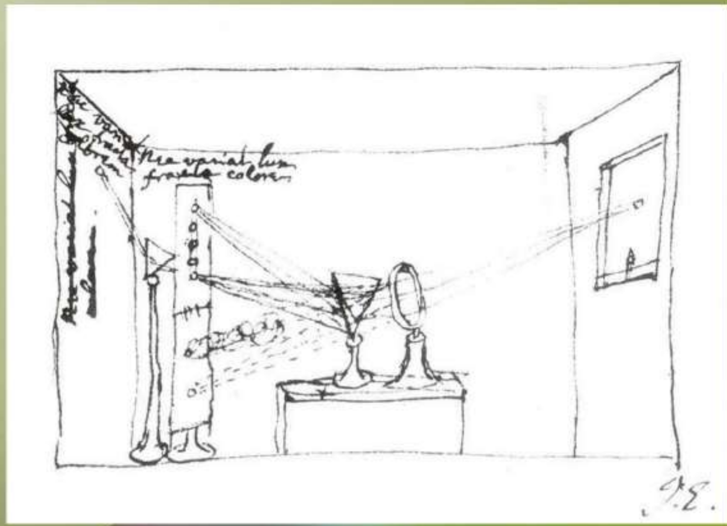
I'm so glad that we are finally thanking these women for the work they did and the ways they transformed the American workplace. These jobs formed an amazing base for people in later years like my dad. When he joined Nasa, he was able to stand on their shoulders. The work that these women did was transformative, not just for them but for their communities, and their children and grandchildren as well. ■

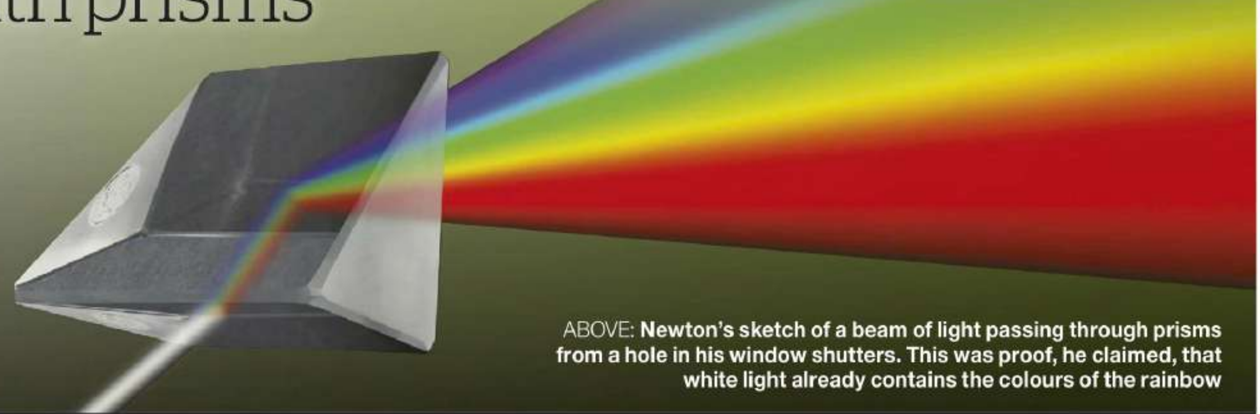
Margot Lee Shetterly (pictured) is the author of *Hidden Figures: The American Dream and the Untold Story of the Black Women Mathematicians Who Helped Win the Space Race*, which inspired the film of the same name. **Ellie Cawthorne** is *BBC History Magazine* staff writer

Science Stories

OPTICS

1672
Isaac Newton announces his experiments with prisms





ABOVE: **Newton's sketch of a beam of light passing through prisms from a hole in his window shutters. This was proof, he claimed, that white light already contains the colours of the rainbow**

Science's greatest legend was launched almost 300 years ago when, shortly before he died, Isaac Newton (1642–1727) told several friends that he had conceived his theory of gravity beneath a tree in his country orchard. Like the attribute of a saint, Newton's apple has become the iconic symbol of a scientific genius forever voyaging through strange seas of thought alone.

Yet when he was elected a fellow of London's Royal Society in his late twenties, Newton was acclaimed not for his theoretical daring, but for his practical expertise.

A skilled craftsman, Newton had created an impressively small yet powerful telescope, painstakingly polishing lenses and mirrors designed to reduce distortion. Views of his own past were less clear cut. When he presented his first paper on prisms in 1672, Newton glossed over the sidetracks and false hopes that are inevitable in any protracted research project. Instead, he made it appear that one single demonstration – a "crucial experiment" – vindicated his ideas and showed beyond doubt that his rivals were wrong.

According to the theory prevailing then, light is altered in its passage through a medium such as air or water: when the sun shines through the stained glass in a church window, or candles make diamonds vibrate with colour, we see light that has been modified during its journey between the original source and our eyes.

In contrast, Newton maintained that the colours of the rainbow are already present in what appears to be white light, and he set out to devise a way of confirming this experimentally. In 1672, he claimed that two ordinary prisms were enough to provide incontrovertible proof that he was right.

Like the supposed flash of inspiration under the apple tree, Newton dated his key experiment in optics back to 1666, a year in which he spent much of his time at his Lincolnshire home after plague forced him to quit Cambridge. In a deceptively chatty letter, Newton explained that he had placed a prism in a beam of light shining through a small hole in his window-shutters, and found it "a very pleasing divertissement, to view the vivid and intense colours produced thereby".

> Newton's results were impossible to replicate, because **he had left out vital details**

After a while – at least, this is how his story runs – he decided to investigate further, and placed a second prism in one of the coloured rays. When the light passed through the glass unchanged, Newton claimed that he had disproved the modification theory of the French philosopher René Descartes.

Newton's experiment was dramatic, but was it crucial? Arguments raged for years. His bitter enemy Robert Hooke accused Newton not only of stealing his own research, but also of failing to produce definitive proof – there were, he insisted, alternative explanations. European experimenters raised another serious objection: Newton's results were impossible to replicate, because he had left out vital details such as the type of glass and the dimensions of the prisms.

Few in England dared contradict Newton's authority, yet as an Italian critic protested, it would be strange if "in places where experiment is in favour of the law, the prisms for doing it work well, yet in places where it is not in favour, the prisms for doing it work badly". Perhaps Newton is not as transparent a hero as he might seem. H *Words: Patricia Fara*

TOPFOTO/ALAMY

FROM ***BBC FOCUS MAGAZINE***

INVENTIONS DISCOVERIES & CONNECTIONS

Disputed discoveries, weird connections and debunked theories: *BBC Focus Magazine* explores some of the most contentious controversies in the history of science

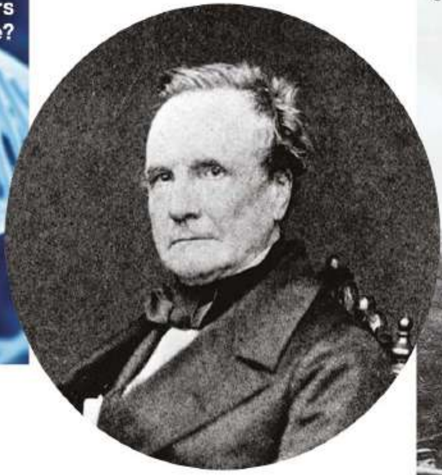
DREAMSTIME

DNA double helix: were Crick and Watson 80 years behind the curve?

Who really discovered... DNA?

Francis Crick and James Watson are the scientists most often associated with the famous genetic molecule, but their work in the 1950s came over 80 years after the identification of DNA by a Swiss physician searching for the 'building blocks' of life. Friedrich Miescher had focused on proteins in cells, but in 1869 he discovered a strange substance also lurking in the nuclei of the cells. He named it 'nuclein', and suspected that it would prove at least as vital to cells as proteins.

Nor were Crick and Watson the first to show that Miescher was right. Their celebrated discovery of DNA's double-helix structure was prompted by key experiments by a team led by the American biochemist Oswald Avery, working at the Rockefeller University in New York. In 1944 these researchers published the results of painstaking studies using bacteria that revealed that DNA passed genetic information from one organism to another. This went against the accepted wisdom that proteins must be the carriers of genetic information, as DNA was 'obviously' too simple a molecule to perform such a complex role. Crick and Watson agreed with Avery – but the latter's claim to a Nobel Prize was blocked by sceptics until the 1960s, long after his death in 1955.



Who really invented... the computer?

Computers are far more than ultra-fast number-crunchers. Based on a set of instructions, a computer's processor and memory can – in principle, at least – perform an almost infinite range of tasks, from word-processing to flying a plane. The first person to consider building such a versatile device was British mathematician Charles Babbage (pictured above), who in 1834 began drawing up plans for what he called an "analytical engine". His vision was to create a device the gears, rods and wheels of which could be arranged – programmed – to perform a myriad of tasks, from solving equations to composing music. Sadly, only a fragment of this Victorian engineering miracle was ever completed.

Just over 100 years later, another British mathematician, Alan Turing, revived the idea of a 'universal machine' and investigated its theoretical powers. During the Second World War, his code-breaking colleagues at Bletchley Park exploited some of these powers. Their electronic device, called Colossus, broke some of the most secret ciphers of the German High Command.

Historians still argue about who built the first genuine computer, but it's generally agreed that by the late 1940s engineers in both the US and Britain had succeeded in creating electronic machines embodying Babbage's dream.

'Big Bertha' – the type of giant howitzer used by Germany in the First World War, pictured here on the western front in 1915 – was among the earliest applications of hard molybdenum steel

What connects ... bacteria with bombs?

All living things need nitrogen to make protein but, before nitrogen in the air can be metabolised, it must first be converted into ammonia by certain bacteria.

These bacteria are essential because they make the nitrogenase enzymes that catalyse the nitrogen conversion. Each nitrogenase molecule contains at its core a single atom of the element molybdenum.

Molybdenum can also be added to steel to make very hard alloys. Construction of the German howitzer known as 'Big Bertha', deployed in the First World War, involved one of the earliest applications of molybdenum steel.

The shells fired by Big Bertha, each of which weighed nearly a tonne, contained the explosive trinitrotoluene (TNT), which is made by reacting nitric acid with toluene. Nitric acid is made from ammonia.

DREAMSTIME/GETTY

Who really discovered... Neptune?

On the night of 23 September 1846, German astronomer Johann Galle noticed an object in the constellation Aquarius that didn't appear on the latest star maps. Its disc-like appearance suggested that it was a planet – a conclusion confirmed the following night by its movement relative to the distant stars.

Galle's discovery of the planet now called Neptune was no coincidence. He had been asked to examine that patch of the night sky by Urbain Le Verrier, a brilliant French theoretician who had been studying strange effects in the orbit of Uranus, and concluded that it was being affected by an unseen planet.

But while Galle and Le Verrier were being hailed for their discovery, British astronomers claimed that a young Cambridge mathematician, John Couch Adams (pictured above), had made similar calculations, and that a British astronomer had subsequently seen Neptune three times – but failed to recognise it. This attempt to grab some of the glory sparked an international row that intensified when American scientists argued that the predictions of both were faulty and the discovery merely a happy accident.

Recent research has led historians to dismiss the British claim. In any case, it's now known that Galle wasn't the first to see Neptune: studies of Galileo's notebooks show that he spotted it as early as 1612.

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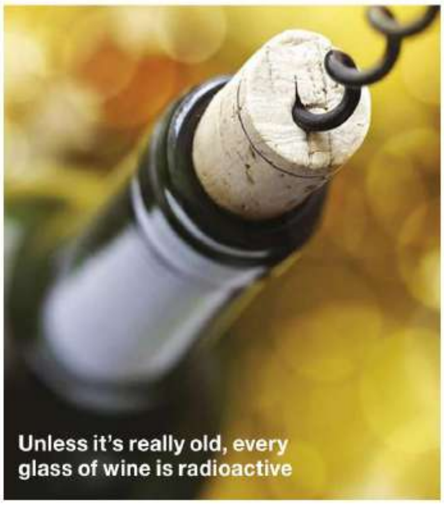


Unless it's really old, every glass of wine is radioactive

What connects ... nuclear weapons with fine wine?

In 1945, the US Army conducted the first nuclear weapons test as part of the Manhattan Project. Since then, there have been more than 2,000 nuclear explosions around the world.

Each nuclear explosion releases several hundred grams of the radioactive isotope caesium-137. This has a half-life of about 30 years, and is not normally found in nature.

Caesium-137 dust from nuclear explosions gets dispersed in the atmosphere and reacts with rainwater to form soluble salts that are absorbed in tiny quantities by plants through their roots.

Any wine bottled after 1945 contains detectable amounts of caesium-137 (though it is quite safe to drink). This fact has been used to test claims of extreme age in bottles of wine.

Any **wine bottled since 1945 contains the radioactive isotope caesium-137** – though thankfully it is quite safe to drink

Frank Whittle (right) explains the workings of his jet engine

Who really invented... the jet engine?

The basic idea of creating motion by directing a jet of fluid in the opposite direction to the desired direction of travel dates back to ancient times. In the first century AD, the Greek mathematician Hero of Alexandria described a device propelled by steam squirted out of two opposing nozzles. However, it's unlikely that it would have worked – the jets were probably too weak to overcome friction between its various components.

In 1922, French engineer Maxime Guillaume was granted a patent for a simple jet engine. Though it was never built, the idea was right. It consisted of a series of turbines that compressed air, which was then mixed with fuel and ignited. The resulting rapidly expanding gas produced thrust.

The first to succeed in making this approach work was a young RAF engineer named Frank Whittle. In the 1920s he devised an arrangement of turbines and compressors that, he claimed, would produce enough thrust for aircraft propulsion. The UK air ministry disagreed, however, so Whittle set up his own company, which produced the first working jet engine in 1937. By then, German physicist Hans von Ohain had hit on a similar solution, and was ahead of Whittle in achieving the first actual flight of a jet aircraft – the Heinkel He 178 – in August 1939.

Sections of the Space Shuttle's boosters travel to Kennedy Space Centre

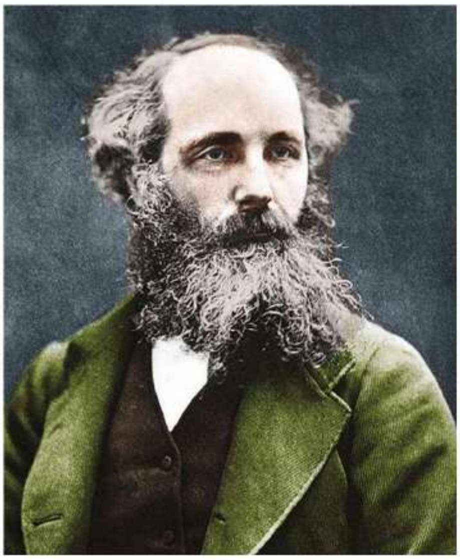
What connects... the Space Shuttle with a pair of horses?

The Space Shuttle's solid rocket boosters were manufactured in Promontory, Utah. Transport to the launch site in Florida, 3,860km (2,400 miles) away, involved a seven-day train journey.

In order to fit through railway tunnels along the route, each booster segment was designed to a maximum diameter of just 3.66m (12ft).

The width of railway tunnels is determined by the gauge of the railway track. The US uses the standard track gauge of 1.44m (4ft 8.5in).

Early trains were drawn by horses. The standard track gauge was based on the width of two horses pulling a cart side by side – a standard that was retained when steam railways were developed, so that the same wagons could be reused.



Who really discovered... radio?

The discovery of radio waves ranks among the most astounding achievements of Victorian science, with far-reaching consequences that are still felt today.

The existence of radio waves was predicted in the 1860s by the brilliant Scottish theoretical physicist James Clerk Maxwell (pictured above). He was developing a theory proposing that electricity and magnetism are different aspects of the same phenomenon. Maxwell's prediction was confirmed in 1887 by the German physicist Heinrich Hertz, who – incredibly – dismissed radio waves as "of no use whatsoever".

Fortunately, other scientists saw potential in the mysterious waves that could travel through air, solid walls and the vacuum of space. Among them were the British physicist Oliver Lodge and the Italian electrical engineer Guglielmo Marconi, who independently invented ways of turning electrical discharges into detectable signals. The two men became involved in several legal battles over patents, but Marconi is now usually regarded as the 'inventor' of radio communication. That's partly because he was the first to send simple radio signals across the Atlantic Ocean – a PR coup that brought him international recognition including a Nobel Prize.

Yet even Marconi failed to realise the full communication potential of radio. Overcoming the technical challenges of creating a high-fidelity speech-and-music medium involved a host of far less well-known inventors.

The flame in Welsbach's lamp was surrounded by a thorium oxide mantle

What connects... gas street lights with nuclear power?

In 1885, Austrian scientist Carl Auer von Welsbach invented a new form of gas lighting that was much brighter than earlier flame lamps.

In the lamp introduced by von Welsbach, the flame was surrounded by a thorium oxide mantle. Thorium oxide has a melting point of 3,300°C. Von Welsbach's mantle could therefore glow white-hot without melting away.

However, thorium is radioactive; it decays to radon-220, which is also radioactive. Using a thorium gas lamp isn't dangerous, but old gas-mantle factory sites suffer problems with contamination.

Thorium is a safer alternative to uranium or plutonium in nuclear reactors. Thorium can't be weaponised, and its high melting point makes it less prone to catastrophic meltdown.

Marconi won the Nobel Prize, but even he failed to realise **the full communication potential** of radio

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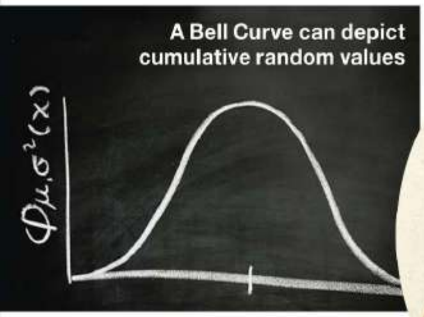


A Bell Curve can depict cumulative random values

Who really described... the Bell Curve?

Named for its central peak and gracefully sloping sides, the Bell Curve is one of the best-known, most-important graph types in maths and science. In mathematical terms, it depicts the normal distribution – the spread of values of anything affected by the cumulative effects of randomness, where the mean ('average') value is the peak, with other, less-common values to either side. From stock market jitters to human heights and IQ, many phenomena follow at least a rough approximation of the Bell Curve.

Many textbooks refer to normal distribution (the Bell Curve) as the Gaussian Curve, honouring the brilliant 19th-century German mathematician Karl Friedrich Gauss, who deduced its shape while studying how data are affected by random errors. However, a French maths teacher named Abraham de Moivre had arrived at the same shape decades earlier, while tackling a problem that had baffled mathematicians for years: how to calculate the frequency of heads or tails resulting from a large number of coin-tosses.

Historians often use the term 'Gaussian Curve' as an example of Stigler's law of eponymy, which states that no scientific discovery is named after the person who actually discovered it.

Who really invented... the periodic table?

On the wall of every school chemistry laboratory is a poster of the periodic table of elements – the go-to reference tool for chemical elements for almost 150 years. The Russian chemist Dmitri Mendeleev (pictured above) is often credited with formulating the rules that define the block-like patterns of elements, even though others had established those rules some years earlier, albeit without recognition for their work.

One of those scientists was John Newlands, an English chemist who in the mid-1860s pointed out that, when arranged according to their atomic mass, elements with similar properties lie close together. However, in describing his findings to fellow scientists he drew parallels with musical octaves, prompting howls of derision. In fact, Newlands' discovery had been presaged by the work of another English chemist, William Odling – though he, too, failed to garner much interest.

Mendeleev's claim to fame lies in the fact that he realised that the patterns were more complex than others had realised. Some columns in his table, first published in 1869, were longer than others. He also suspected that gaps within the resulting blocks implied the existence of as-yet undiscovered elements, and bravely attempted to predict their properties. His confidence was vindicated with the discovery of gallium, germanium and scandium, securing his place among the great names of 19th-century science.

US soldiers in the Vietnam War were the first patients whose wounds were sealed with cyanoacrylates

What connects... gun sights with wound sutures?

In 1942, during the Second World War, American chemist Dr Harry Coover was researching clear plastics that could be used in the manufacture of lightweight gun sights. One of the chemical groups he tested was the cyanoacrylates.

Coover discarded cyanoacrylates as a suitable material for gun sights because they bond instantly to almost anything. But in 1958 the company where he worked, Eastman Kodak, took advantage of this property to market a cyanoacrylate as an adhesive, selling it as Eastman #910, later renamed Super Glue.

Cyanoacrylates are liquids at room temperature, but the presence of even a tiny amount of moisture causes cyanoacrylate molecules to link rapidly into a long, sticky chain.

In 1966, field medics in the Vietnam War used a cyanoacrylate spray to temporarily seal wounds. Today, medical-grade superglue is used to repair small cuts.

DISCOVER MORE

MAGAZINE

▶ These answers originally appeared in ***BBC Focus Magazine.*** Read more fascinating Q&As in each issue or online: *sciencefocus.com*

DREAMSTIME/GETTY

Marcus du Sautoy on... **the importance of the history of maths**

"History can be a powerful ally in teaching difficult mathematical ideas for the first time"

When I learnt my mathematics at school it was taught in a very ahistorical manner. The people, the cultures, the politics were all missing. It was the ideas that counted. I learnt how negative numbers worked. What to do with a sine and a cosine. How to calculate volumes of solids. I knew little of the history of these ideas. Personally, the abstract ideas were enough to excite me, but the missing stories of where these ideas came from could have engaged so many more in the wonders of mathematics.

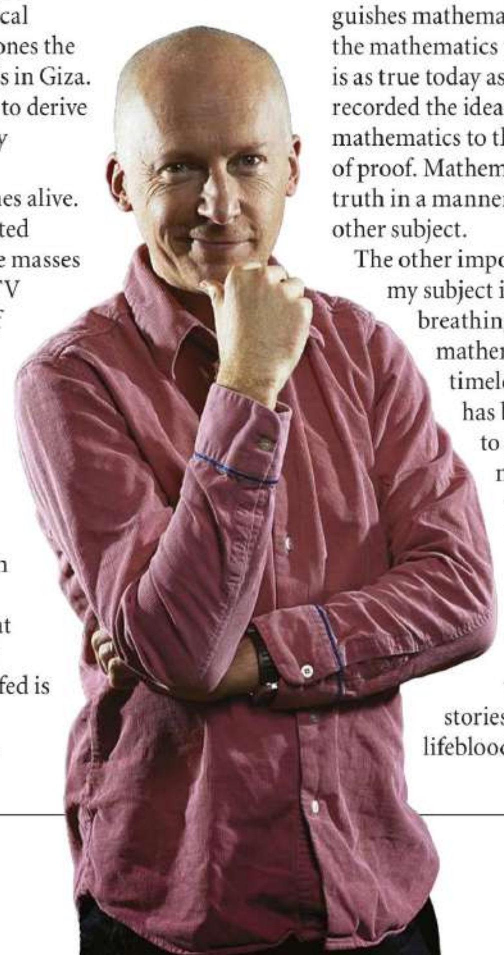
For example, sines and cosines were our best tools for navigating the night sky centuries before Galileo ever had a telescope in his hands. The ancient Greeks could use triangles and angles to tell the relative sizes of the earth, moon and sun without ever leaving the comfort of their observatories. I think that knowing this history gives life to concepts that might otherwise feel like they're invented to torture students at exam time.

Or take the formula for the volume of a pyramid. You could simply learn that it's a third of the area of the base times the height. Or you could show students the Egyptian papyrus where this formula first appears. The scribe was motivated by the very practical challenge of wanting to know how many stones the architects would need to build the pyramids in Giza. The papyrus also contains the ideas of how to derive the formula by approximating a pyramid by constructing a tower of rectangular boxes. Suddenly, with context, a dry equation comes alive.

I must admit that it was only when I started exploring ways to bring mathematics to the masses through the books I have written and the TV programmes that I have made that I myself became aware of where my subject came from. In 2008 I made a series for the BBC called *The Story of Maths*. It charted in four one-hour episodes the origins of mathematics in ancient Egypt and Babylon, through to the amazing breakthroughs of the last century that are the ingredients for the technological revolution we all enjoy today.

It was while making that programme that I understood how Eurocentric our view of mathematics is. The story most people are fed is that mathematics began with the ancient Greeks and then went quiet until its resurgence during the Renaissance. But I discovered how much exciting mathematics was being done in India long before Fibonacci (c1175–c1250) kickstarted the mathematical revolution in Europe, and that there were inklings of the calculus bubbling away in India in the 14th century, well before Newton and Leibniz articulated their theory. But these historical vignettes aren't just interesting curiosities.

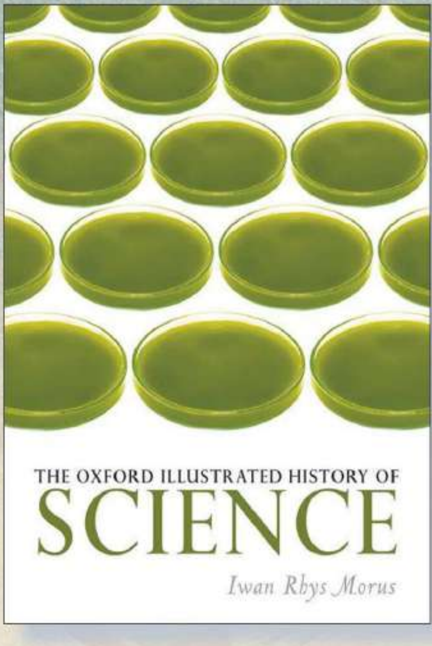
Marcus du Sautoy is the Simonyi professor for the public understanding of science, and professor of mathematics at the University of Oxford, and the author of *What We Cannot Know* (Fourth Estate, 2017).



Witnessing the way teachers have used excerpts from the *Story of Maths* in the classroom, I've seen how history can be a powerful ally in teaching difficult mathematical ideas to those encountering them for the first time. A historical perspective has even helped me in my own journey to create new mathematical knowledge – appreciating how a completely new mathematics appeared from the old has given me the tools to make my own breakthroughs.

A historical narrative is actually hiding beneath the educational trajectory we take students on as they learn their mathematics. It's not dissimilar to building those pyramids in Giza. Each year at school we construct a new layer of the edifice on top of the ideas we encountered before. And this is exactly how mathematics evolved through history. What distinguishes mathematics from the rest of science is that the mathematics that was discovered 2,000 years ago is as true today as it was when the likes of Euclid recorded the ideas in his *Elements*. The resilience of mathematics to the effects of time is due to the power of proof. Mathematical proof allows us to access truth in a manner that is almost impossible in any other subject.

The other important role that history can play for my subject is to reveal that it is still a living, breathing subject. For most students, mathematics seems to live in some timeless, never-changing textbook that has been handed down from generation to generation. With such a picture, it's no wonder that many don't realise that there are so many chapters of the mathematical story still to be written. What gets me up in the morning to run to my desk are all the unsolved problems. It's the mathematical enigmas – those whose solutions will become the stories of tomorrow – that are the lifeblood of mathematics. H



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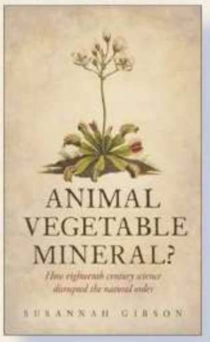

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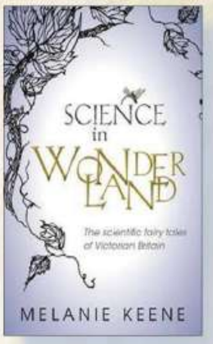

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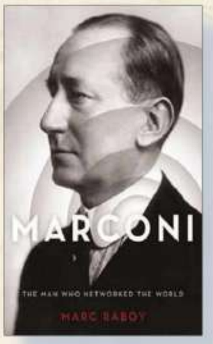

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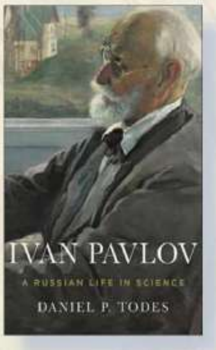

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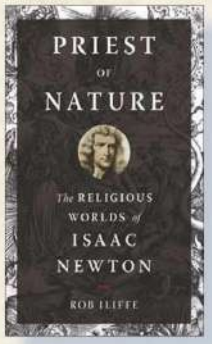

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